Master's Thesis – master Sustainable Development

Nature Based Solutions for Carbon Sequestration and Biodiversity Conservation: Is there a future for solutions that look beyond tree planting for forests and grassy biomes?

Picture: Cullen (2021)

Emma Leltz
6623646

Master Sustainable Development
Track Environmental Change and Ecosystems

Supervisor: Mariska te Beest

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Summary

Natural climate solutions (NCS) are increasingly proposed as promising measures to reduce greenhouse gas concentrations and mitigate climate change by conserving, restoring and managing natural ecosystems. Plans to implement them are included in ecosystem restoration commitments that governments make in order to reach greenhouse gas emission targets. A concern is that implementation of these plans will not result in restoration of the native ecosystem, but in monoculture tree planting programs. These plantations can endanger native vegetation and negatively impact livelihoods of local communities. Grassy biomes are claimed to be particularly at risk of degradation as a result of tree planting projects. It is argued grassy biomes are falsely defined as degraded forests, and a bias towards forests and trees causes solutions that would be more suitable for these ecosystems to be overshadowed. Rather than focusing on numbers of trees that are planted, researchers suggest to design solutions that provide synergies between climate change mitigation, biodiversity conservation and contributing to sustainable livelihoods.

This research aims to get insights into which natural climate solutions are related to ecosystem restoration commitments made by governments, and the extent to which they could lead to afforestation in ecosystems that would not be suitable for tree planting. This is done by a quantitative analysis in which restoration commitments per country are inventoried, and commitments for forest increase are compared to the forest land available for restoration according to different maps.

Moreover, a literature research is done with the aim to inventory proposed and implemented natural climate solutions beyond tree planting, and evaluate them on their potential to contribute to climate change mitigation, biodiversity conservation and sustainable livelihoods.

The results show restoration commitments for different ecosystems. As expected, there are more and larger commitments related to forest ecosystems than to grassy biomes. In total 33 countries have committed to increase forest by a larger area than would be possible according to the land they have available for forest restoration. These countries are mainly situated in Sub-Saharan Africa and largely covered by tropical grassy biomes.

In the reviewed articles, a variety of NCS is proposed and their estimated climate change mitigation potential varies widely between different studies. In the case studies used to evaluate NCS for forests and grassy biomes, natural regeneration, fire management, grazing management and agroforestry report positive impacts on at least two of the aspects climate change mitigation, biodiversity conservation and sustainable livelihoods.

Preface

This thesis was written as part of the Master programme Sustainable Development, which I followed in the track Environmental Change and Ecosystems at the University of Utrecht. The topic of this research was provided by my thesis supervisor Mariska te Beest, who has helped me set up the research. I would like to thank her for the detailed feedback and useful meetings that helped me keep on track, focus on the right topics and finish this report.

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Introduction

Nature Based Solutions (NbS) are increasingly promoted as a promising concept to work with nature to address social, environmental and economic challenges (Nesshöver et al., 2017). According to many, NbS have the potential to address both the biodiversity and climate crises (Brears, 2020; Chausson et al., 2020; Seddon et al., 2021). Within NbS, Natural Climate Solutions (NCS) focus specifically on mitigating climate change and limiting global warming. If implemented, they are claimed to be able to increase carbon storage by substantial amounts (Griscom et al., 2017). Griscom et al. (2017) argue NCS can provide 37% of the CO_2 mitigation needed until 2030. NCS include restoration and conservation of ecosystems and improved land management. In the context of the UN Decade of Ecosystem Restoration (UNEP, n.d.), that runs from 2021-2030, the Sustainable Development Goals (UNDP, 2021), and other conventions and initiatives, many countries have made commitments to restore ecosystems. Many of these restoration targets also aim to mitigate climate change by reducing greenhouse gases (Suding et al., 2015). In this way, projects to achieve these targets are natural climate solutions. NCS cover a wide range of measures such as restoring natural ecosystems by natural regeneration, management of agricultural land by reduced tillage, and tree planting in both natural and agricultural areas. If managed in the right way, NCS could go alongside with increasing biodiversity and improving the quality of soils, air and water (Griscom et al., 2017).

However, when not managed properly and not accounting for social and ecological impacts while designing these projects, NCS can result in negative consequences. Tree planting, for example, is an NCS that is advocated to be implemented on very large-scales (Bastin et al., 2019), but is widely criticised by scientists (Veldman et al., 2015a; Bond et al., 2019; Temperton et al., 2019; Holl & Brancalion, 2020; Tölgyesi et al., 2021). A concern is that tree planting is often seen as a synonym to ecosystem restoration and thus used to reach targets for land to be restored, while in reality often non-native and biodiversity poor plantations are planted. Lewis et al. (2019) revealed that 45% of the commitments to 'restore' forests in fact cover plantations of monocultures. Planting monocultures results in biodiversity loss (Kemppinen et al., 2020), and ecosystems becoming less resilient and less capable of sequestering carbon (Sakschewski et al., 2016). As Fleischman et al. (2020, p.950) describe, 'Natural climate solutions that count saplings rather than address both the ecological and social drivers of ecosystem destruction are unlikely to succeed.'

Another problem with the promotion of tree planting is that some of the selected areas were not originally covered by forests. Studies select areas with lower tree cover as potential to become forests (WRI, 2014; Bastin et al., 2019). These areas are often classified as degraded forests, while they also include intact grasslands and savannas with a naturally lower tree cover (Hajdu et al., 2016; Hobbs, 2016). Thus, planting trees there should be classified as afforestation rather than reforestation. Afforestation, planting trees in an ecosystem that was not originally a forest, may lead to degradation instead of restoration. Instead of restoring a forest, a natural non-forest ecosystem is degraded. Grassy biomes are non-forest ecosystems with a lower tree cover than forests. They comprise woodlands, savannas and grasslands, ancient ecosystems that are open and in which herbaceous species are dominant (Silveira et al., 2020). Although their value is not always acknowledged, grassy biomes have important ecosystem services that are critical to human livelihoods (Parr et al., 2014; Veldman et al., 2015a; Ramprasad et al., 2020). Tropical grassy biomes (TGBs) cover large areas of the Global South, that is targeted by many tree planting programs (Lele, 2020). TGBs are argued to be particularly in danger of being afforested. They often suffer from misleading definitions that are inconsistent, and lead to false assumptions that trees will improve these ecosystems (Parr et al., 2014). Restoring grasslands after afforestation is nearly impossible and can take centuries (Buisson et al., 2018). Therefore, planting trees in grasslands and savannas can cause these ecosystems to degrade permanently and threaten biodiversity (Abreu et al., 2017).

Although the restoration of a variety of ecosystems has the potential to function as a NCS and enhance ecosystem services in a sustainable way (Strassburg et al., 2020), NCS suitable for non-forest ecosystems can be overshadowed by a focus on tree planting. Temperton et al. (2019) argue there is a bias towards trees, meaning the assumption is that forest ecosystems have the best potential to mitigate climate change. An example of a study that focuses solely on the potential of trees to sequester carbon, is 'The global tree restoration potential' by Bastin et al. (2019). They suggest the Earth has 0.9 billion hectares of additional space for canopy cover and restoring trees there could sequester 205 gigatonnes of carbon. This estimate has been criticised by other researchers for being too large by a factor of five (Veldman et al., 2019). As Veldman et al. (2019) explain, Bastin et al. (2019) assume that areas with low tree cover, including grasslands, do not store carbon. However, whereas forests store a large amount of carbon aboveground, in grasslands the majority of carbon is stored belowground, resulting in high soil organic carbon. Because of this belowground carbon, grasslands can serve as a safe and reliable carbon sink when fire occurs (Dass et al., 2018). Particularly in the context of climate change and increasing risk of droughts and fire, it is important to incorporate this risk. As aboveground carbon could be released during fires, this makes the mitigation potential of forests more uncertain (Anderegg et al., 2020).

In summary, although natural climate solutions have potential to provide a win-win situation for climate mitigation and biodiversity conservation, attempts to implement them can be controversial and may lead to ecosystem degradation instead of restoration. Large scale implementation of natural climate solutions focusses on forests and planting trees, while the restoration of other ecosystems also has potential to contribute to climate change mitigation. Environmental policy plans reflect the popularity to increase forest cover (Galatowitsch, 2009), and natural climate solutions focusing on forest restoration and tree planting projects are increasingly adopted by governments (Chausson et al., 2020). The Bonn Challenge is a well-known example that was initiated in 2011 by the German Government and the International Union for Conservation of Nature (IUCN). It aims to restore 350 million hectares of degraded land globally by 2030 (IUCN, 2020), with an emphasis on forests and tree planting commitments. Furthermore, the EU's Green Deal recently attributed an important role to planting forests to reduce carbon emissions and aims to plant three billion trees by 2030 (European Commission, 2021). The concern is that these targets will not result in restoration of ecosystems, but that they are simply carbon offset policies that distract from emission reductions and that will result in tree plantations, threatening biodiversity and, particularly in the Global South, negatively impact sustainable livelihoods (Foley, 2021; Holl & Brancalion, 2020).

In this research, an inventory will be made of commitments governments make to use restoration projects as a natural climate solutions. By analysing the relation of these commitments to the area in grassy biomes and forest ecosystems, the aim of this research is to conduct a quantitative comparison between forest restoration commitments and area that would actually be suitable for this. Secondly, this research aims to investigate which natural climate solutions beyond tree planting have been suggested or even been implemented, and will evaluate these based on their contribution to, 'climate mitigation', 'biodiversity conservation' and 'sustainable livelihoods'. These three criteria are put forward by many researchers to be crucial for restoration efforts to be successful.

Research questions

In order to achieve the aims of this research, the following research questions are defined:

Research question 1: What natural climate solutions do governments commit to with the aim to reach emission- and restoration targets and do they lead to afforestation of non-forest ecosystems?

1.1 What commitments have governments made for tree planting and restoration of ecosystems?
1.2 How do these commitments relate to the amount of land countries have available for forest restoration?

Research question 2: What natural climate solutions beyond tree planting have potential to be implemented in the future for forest- and grassland ecosystems?
2.1 What solutions besides tree planting programs are currently proposed and to what extent are they already adopted or do they have the potential to be implemented?
2.2 To what extent do these solutions facilitate synergies with conserving biodiversity and providing ecosystem services to local livelihoods?

Theory

In this chapter, the literature from the introduction will be further explained and other relevant theory will be elaborated on. After this, concept definitions are given, relations between the concepts are described and hypotheses are formulated.

Tree cover and the degradation and restoration and of forests and grassy biomes

Tree cover indicates the density of trees in an area, and can be expressed is a percentage, with 0% being an area with no trees and 100% being a completely closed canopy. It is a characteristic that is often used to distinguish between the natural ecosystems forests and grassy biomes (Hirota et al., 2011). Grassy biomes are ecosystems that have no closed canopy tree layer, and thus permit sunlight to reach the surface and allow shade intolerant grasses to cover the ground layer (Lehman et al., 2019). Forest ecosystems, on the other hand, have a dense, closed canopy (Hoffman et al., 2012). In many parts of the world, different biomes with widely varying tree cover states can exist under the same climate (Bond, 2005). Forests, savannas and grasslands can be found alongside each other as alternative stable states in many tropical areas (Staver et al., 2011). Therefore, often areas that are now natural grasslands or savannas could also support a dense forest cover. In that case, the low tree cover is not determined by climate or human intervention, but is maintained by natural fires and herbivores. These non-human consumers can determine the distribution of grasslands and forests in 'ecosystems uncertain', areas that have the climate to support both grassy biomes and forests (Bond, 2005). A positive feedback between fire and vegetation maintains the distribution of forests and grassy biomes (Hoffman et al., 2012). Fire and herbivores reduce the tree cover, keep the system open, and allow flammable grasses to grow. In a system with dense tree cover, on the other hand, fire spread is suppressed (Archibald et al., 2005).

Land degradation can be defined as a loss of ecosystem services as a result of human-induced processes (Olsson et al., 2019). Deforestation is an example of a process that results in degradation of forest ecosystems. In that case, loss in tree cover can indicate degradation of an intact forest after forest clearing by humans. Increasing tree cover can reforest and restore the area again. For natural grasslands, on the other hand, low tree cover can also be a characteristic of the native ecosystem. In these ecosystems, increasing tree cover would degrade the ecosystem by afforestation or woody invasion (Jackson et al., 2002). This shows the difficulty with using tree cover to assess the level of ecosystem degradation and plan reforestation, as a similar tree cover can indicate both a degraded forest, or be a characteristic of an ecosystem with a naturally low tree cover. Therefore, some scientists argue that the conventional view that tree cover is only determined by climate and human caused degradation needs to be reconsidered (Pausas & Bond, 2019).

Carbon sequestration in Natural Climate Solutions for forests and grasslands

In using forest expansion to sequester carbon, carbon is captured from the atmosphere and stored in aboveground biomass (Cook-Patton et al., 2020). This idea is used when tree planting is implemented as a strategy to reduce greenhouse gases in the atmosphere. Around the equator, where many tree planting projects are planned, trees grow fast and sequester carbon at high rates (Lewis et al., 2019).
In addition to aboveground carbon, soil organic carbon (SOC) plays an important role in storing carbon (Guo & Gifford, 2002). According to Bossio et al. (2020) 25% of NCS' climate mitigation potential can be provided by storing carbon in soils. In addition to this, SOC can enhance ecosystem services by improving soil quality. However, Bossio et al. (2020) argue belowground carbon is incorporated less often in natural climate solutions because it is more difficult to measure and there are still unclarities in how to implement it as NCS. Similarly, Veldman et al. (2019) argue SOC is overlooked in the carbon capture estimates by Bastin et al. (2019) that promote tree planting. In grasslands and savannas, the largest part of carbon storage happens belowground (Veldman et al., 2019). Thus, when belowground carbon is neglected and more

attention is given to aboveground carbon sequestration, climate mitigation potential of grassy biomes is underestimated.

Natural climate solutions can be based on conservation, restoration or management of ecosystems (Griscom et al., 2017). Biodiverse, existing natural forests store large amounts of carbon (Pan et al., 2011; Watson et al., 2018), part of which is irrecoverable after release (Goldstein et al., 2020). Disturbance can release this carbon and thus avoiding this can be a natural climate solution. Besides avoiding emissions, protecting intact forests can also store additional carbon. Although some assume old-growth forests are just carbon sinks, Luyssaert et al. (2008) demonstrate these forests can also sequester carbon.

In an ecosystem that is no longer intact, it is argued natural regeneration is more effective than afforestation (Lewis et al., 2019). Lewis et al. (2019) describe that natural forests sequester 40 times more carbon than plantations. It is also claimed that enhancing biodiversity improve ecosystem services, including carbon sequestration (Sakschewski et al., 2016; Osuri et al., 2020). Therefore, protecting intact ecosystems or naturally regenerating a native ecosystem could be more effective as NCS than monoculture plantations.

Natural climate solutions that contribute to biodiversity conservation and sustainable livelihoods

Natural climate solutions use nature to mitigate climate change (Griscom et al., 2017). Although natural processes are used, they do not necessarily maintain the natural ecosystem. As mentioned before, that is why fast-growing tree plantations that are non-native are often criticised (Seddon et al., 2019). Restoring natural ecosystems is better for biodiversity conservation and can meanwhile be cost effective (Seddon et al., 2020). Often the combination of incorporating social and ecological aspects is put forward as a solution for carbon sequestration projects to be successful on the long term (Lewis et al., 2019; Fleischman et al., 2020; Di Sacco et al., 2021). Many have developed guidelines or requirements for restoration projects to achieve this. Chazdon (2008) presents the restoration staircase, in which the less degraded a landscape is, the more cost-effective it will be to restore it and the more biodiversity and ecosystem services will be gained. Therefore, natural regeneration, assisted natural regeneration and reforestation with native trees are favoured over commercial reforestation, agroforestry, rehabilitation and reclamation. Di Sacco et al. (2021) also recommend using natural regeneration when it is possible as one of the 'golden rules' for restoration that contributes to carbon sequestration, biodiversity conservation and sustainable livelihoods. If natural regeneration is not possible, mixed and native species should be used. They further recommend to work together with local communities and only select areas that were previously forested to establish forests on. Like Di Sacco et al. (2021), Duguma et al. (2020) also advise to involve local communities in restoration projects, as there is currently a gap in what communities want and the projects that are executed. Fischer et al. (2019) use the concept of distant interpretations to argue that projects such as carbon forestry can negatively impact livelihoods if designed far from the place where they are implemented. Mapping can, for example, falsely describe land as degraded and select it for restoration while the local population uses many of its ecosystem services.

Impact on water and other ecosystem services

Ecosystem services are 'the suite of benefits that ecosystems provide to humanity' (Cardinale et al., p.60), for example regulating climate and providing fresh water. Carbon sequestration is thus an ecosystem service. When using NCS to sequester carbon, the implementation can result in a trade-off for other ecosystem services. An ecosystem service that is often argued to be influenced by forestation, is water supply (Bonnesoeur et al., 2019). Jackson et al. (2005) demonstrate tree plantations can have negative effects on groundwater, stream flow and water quality. By analysing tree plantations that were designed for carbon offset programs, they show how afforestation decreased stream flow and caused some streams to dry up.

In short, ecosystem services can influence each other. In the same way as the Sustainable Development Goals, they should be integrated and not treated separately when designing NCS (Seddon et al., 2020).

In figure 1, the relations between the concepts and the research questions are visualised. The definitions of used concepts are given in table 1. It should be mentioned that in this research natural ecosystems are studied. NCS for urban areas are excluded.

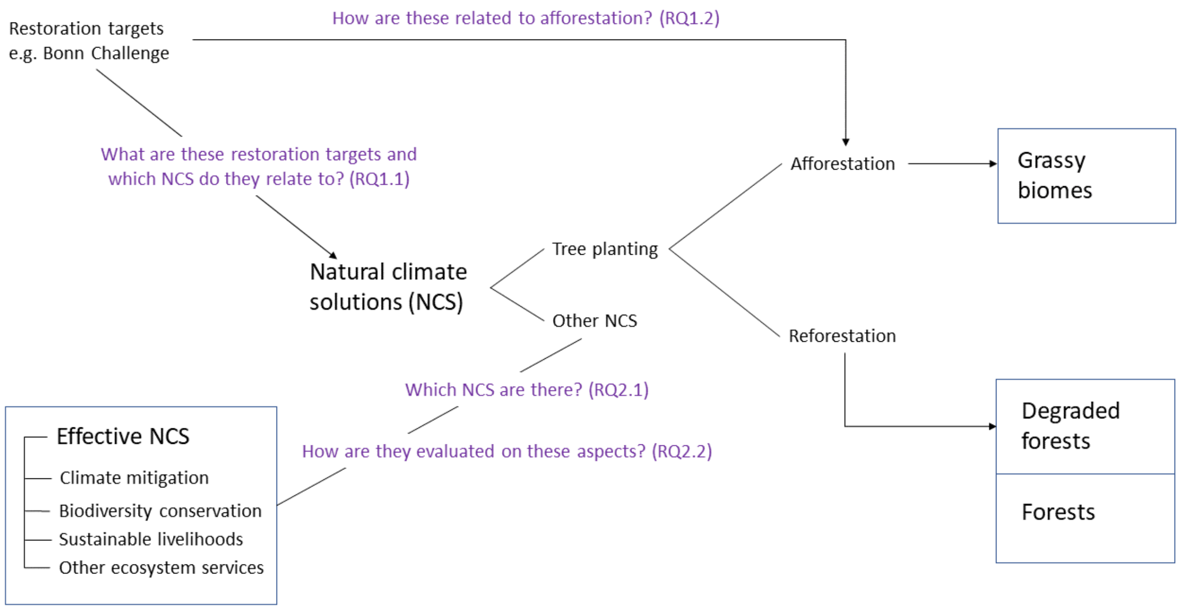

Figure 1: Relations between concepts and research questions.

Hypotheses

Using the literature in the theory section described above, the following hypotheses are formulated:

RQ1: **Most of the restoration targets will be focussed on reforestation rather than alternative NCS or restoration of other ecosystems. The largest commitments will be found in the Global South and countries with more forest land available will have made larger commitments.**

Governments are expected to have made restoration pledges in order to mitigate climate change, that will emphasise forest restoration. Countries that have made commitments to reforest or afforest large areas, will have more land available that supports forest cover. This land is comprised of both degraded forest and land situated in non-forest ecosystems that naturally has sparser tree cover. Hence, there will be countries that have pledged to increase forest cover by more hectares than they have area available in forest ecosystems. Many of these countries are expected to be situated in the Global South and covered for a large part by tropical grassy biomes.

RQ2: Most literature will be focused on NCS in the form of reforestation and afforestation. NCS that incorporate social and ecological factors will most often be evaluated to have synergies between climate mitigation, biodiversity conservation and sustainable livelihoods.

Natural climate solutions beyond tree planting are expected to comprise different ways of forest restoration and restoration of other ecosystems. Restoration of non-forest ecosystems is expected to be implemented on a smaller scale than reforestation, and also less represented in literature. Furthermore, in literature that compares NCS, reforestation and other NCS for forest ecosystems is expected to be more promoted to sequester carbon than NCS for grassy biomes. Within forest solutions, protecting forests is expected to be described as most effective, followed by natural regeneration. Regarding case studies of implemented NCS, it is expected there will be more case studies that report negative social and ecological impacts of tree planting or afforestation than other NCS. NCS that focus on social and ecological factors on the other hand, are expected to have more synergies between climate mitigation, biodiversity conservation and sustainable livelihoods, so it is expected that case studies that report a positive effect for one of the aspects, will also report positive impacts on the other aspects.

Concept	**Definition**
Grassy biomes	Ecosystems that have no closed canopy tree layer, and thus permit sunlight to reach the surface and allow shade intolerant grasses to cover the ground layer (Lehman et al., 2019). Includes the following terrestrial ecoregions (Olson et al., 2001): - Tropical and subtropical grasslands, savannas, and shrublands - Temperate grasslands, savannas and shrublands - Flooded grasslands and shrublands - Montane grasslands and shrublands
Forests	Ecosystems with a closed canopy tree layer Includes the following terrestrial ecoregions (Olson et al., 2001): - Tropical and subtropical moist broadleaf forests - Tropical and subtropical dry broadleaf forests - Tropical and subtropical coniferous forests - Temperate broadleaf and mixed forests - Temperate coniferous forests - Boreal forests/taiga
Tropical grassy biomes (TGBs)	Grassy biomes in tropical and subtropical regions, defined by the area in the terrestrial ecoregion 'tropical and subtropical grasslands, savannas, and shrublands' (Olson et al., 2001).
Forest land available	The amount of area a country has in the forest ecoregions. This includes deforested areas that are used for agriculture or urban areas that were originally forested, but are not forests anymore.
Land available for forest restoration	The amount of forest land a country has , that is not intact forest, as intact forest would not have to be restored.
Nature Based Solutions (NbS)	Protecting, managing or restoring natural or managed ecosystems with the goal to tackle a societal challenge (Cohen-Shacham et al., 2016)
Natural Climate Solutions (NCS)	Nature Based Solutions that aim to mitigate climate change (Griscom et al., 2017).

Reforestation	Planting forests on land that was originally a forest but was deforested by humans (Veldman et al., 2015b)
Afforestation	Planting trees on land with naturally low tree cover that was not originally covered by forest (Veldman et al., 2015b).
Tree planting	Planting trees in a natural or managed ecosystem, including reforestation and afforestation (Veldman et al., 2015b)
Ecosystem services	'The suite of benefits that ecosystems provide to humanity' (Cardinale et al., 2012, p.60)
Sustainable livelihoods	´A livelihood comprises the capabilities, assets (including both material and social resources) and activities required for a means of living. A livelihood is sustainable when it can cope with and recover from stresses and shocks, maintain or enhance its capabilities and assets, while not undermining the resource base.' (Scoones, 1998, p.5)
Biodiversity	The variety of life in an ecosystem (Cardinale et al., 2012)
Climate change mitigation	Reducing the effects of climate change by limiting global warming (Griscom et al., 2017)

Table 1: Definitions of concepts used in this research

Methods

Below, the quantitative and qualitative methods that were used to answer the research questions are explained.

Inventory of commitments for natural climate solutions

The first research question investigates which nature based solutions are currently planned for climate change mitigation. This research focusses on nature based solutions that are described as restoration projects in policy and are defined as quantitative commitments, such as tree planting, reforestation and restoration of other ecosystems. Desk-based research was conducted to inventory the commitments and pledges governments have made to restore ecosystems and plant trees in order to mitigate climate change.
Restoration commitments were assembled for 117 countries based on the following resources:

- The Global Restoration Commitments (GCR) Database (Sewell et al., 2020) is a comprehensive database that was made by the Netherland Environmental Assessment Agency (PBL). It lists national commitments that are quantitative and publicly available, and were set under the UNFCCC, CBD and UNCCD. These are the United Nations Rio Conventions, that countries can voluntarily submit plans for to combat climate change, land degradation and biodiversity loss. In addition to these conventions, targets for the Bonn Challenge and related regional initiatives are included. The GCR database was used to investigate the commitments per countries in different categories. It specifies restoration commitment for different ecosystems. The database includes restoration commitments for 115 countries and provides several estimates for the total restoration area per country. In this research, 'middle estimate 1' was used. The GCR database does not include commitments in national policies.
- To supplement the GCR database, a useful resource is the InfoFLR database (IUCN, 2018). It provides national restoration targets for 33 countries, retrieved from national environmental policies. In the database, quantitative national restoration targets for 33 countries can be found.
- The website of the Bonn Challenge (IUCN, 2020) also lists restoration targets per country. These targets are already included in the GCR database. The websites of the related initiatives AFR100 (AFR100, n.d.) and Initiative 20x20 (Initiative 20x20) are used to inventory which projects are realised as a result of the Bonn Challenge to address the second research question of this research.

Comparing restoration commitments to forest land available

Subsequently, the restoration commitments were compared to the area each country has in forests and grassy biomes. This was done using several maps. ArcGIS Pro was used to calculate overlapping areas on the different maps. The coordinate system used is WGS 1984.
The following data sources were used:

- **Forest commitments**: The commitments per country were retrieved using the databases described in the previous paragraph. The GCR database, the commitments in the categories 'forest increase and 'forest restoration' were assembled. From the FLR database, the total restoration commitment per country is taken, as this database focuses specifically on forests. For countries that had forest commitments in both databases, the highest of the two was taken.
- **Countries**: A topographic world map from Esri (Esri, 2021) providing shapefiles of 228 countries. By analysing the intersection of this map with the other maps, the area per country could be calculated for the variables listed below:
- **Area in forests and grassy biomes**: The WWF terrestrial ecoregion map (Olson et al., 2001) is used to define forests and grassy biomes. This map served as a basis to relate all the results to. It divides the world's terrestrial surface into 14 ecoregions, of which 6 were defined as forests, and 4 as grassy biomes (table 1).
- **Forest land available**: This is the area per country in forest ecoregions (table 1).

- **Land available for forest restoration**: This was calculated by taking the forest land available, and subtracting the area of intact forests per country (function 2). After all, these areas would not have to be reforested. To calculate the area intact forests per country, the anthromes concept was used (Ellis et al., 2010), that maps which areas are 'wild', 'semi-natural', or 'intensively used' , and can also be loaded in ArcGIS using the HYDE 3.2 database (Klein Goldewijk, 2017). To calculate the intact forests per country, area in the wild anthromes in 2017 was used. The overlap of wild anthromes and the forest ecoregions was defined as 'intact forests', and calculated per country.

Using the variables described above, the relation between forest land in each country was plotted against the forest commitments per country.

$$Land\ available\ for\ forest\ restoration\ (km^2) = Forest\ land\ avaliable(km^2) - Intact\ forests(km^2)$$

Function 1

Finally, the surplus of forest commitments was calculated by subtracting the forest commitments from the land available for forest restoration (function 2). This gives an indication of which countries have committed to restore or increase more forest area than they have forest land available for restoration.

$$Surplus\ forest\ commitments = Land\ available\ for\ forest\ restoration\ (km^2) - Forest\ commitments(km^2)$$

Function 2

Alternative distributions of forests and grassy biomes

To provide an additional perspective of alternative biome states, the ecosystems uncertain concept by Bond (2005) was used. To acquire a shapefile of areas that support both forests and grassy biomes in ArcGIS, the ecosystems uncertain map was redrawn in MATLAB (figure 2). This was done using climate data from WorldClim (WorldClim, 2020), and the function provided by Bond (function 3). The climate data comprises of average data for precipitation and temperature in the period 1970-2000 at a resolution of 30 seconds.

$$MAP > 7.143 * MAT\ +\ 286\ and\ MAP <\ -1.469 * MAT^2 + 81.665 * MAT + 475$$

Function 3: requirements for Mean Annual Precipitation (MAP) and Mean Annual Temperature (MAT) to support both forests and grassy biomes (Bond, 2005)

The ecosystems uncertain map was used to generate alternative scenarios in which forests would be maximised, or grassy biomes would be maximised. A map with maximum forest cover was made by using the current forest cover of the WWF terrestrial ecoregions map and assuming all ecosystems uncertain would also be forests, and the same is done for grassy biomes. With these maps of maximum forest- and grassy biome cover, the same calculations as in the previous step were performed to calculate which countries do not have enough forest land to realise commitments for forest increase.

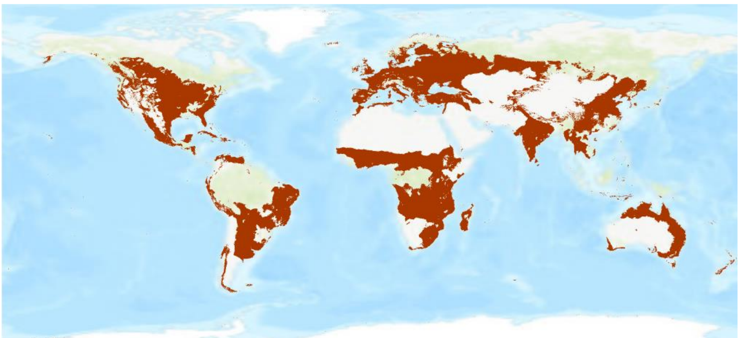

Figure 2: Ecosystems uncertain, redrawn using the article by Bond (2005)

All input maps used in the analysis can be found in appendix 1.

Grassy biomes classified as degraded

A map that is often used in the literature on deforestation, but is criticised for describing non-forest ecosystems as deforested (Bond, 2016; Kemppinen et al., 2020), is the Atlas of Forest Landscape Restoration Opportunities (WRI, 2014). This map was also analysed in ArcGIS to calculate how much overlap it has with each of the terrestrial ecosystems.

Literature research on natural climate solutions beyond tree planting

To make an inventory of natural climate solutions that are proposed and implemented, literature was searched using the bibliography of the Nature Based Solutions Initiative (University of Oxford, 2021). This database contains 487 articles that can be filtered on the challenge that they address. By filtering on the goal 'climate change mitigation', Natural Climate Solutions are filtered. This resulted in 141 articles. These articles were further scanned on title and abstract to select NCS relevant for forests and grassy biomes and studies that only focus on marine, coastal and wetland ecosystems were excluded. The remainder of the articles were used for either inventorying proposed NCS, or evaluating NCS with case studies. Seven of the articles were useful for listing proposed NCS, as they provide an comparative overview of NCS and their climate mitigation potential.

Furthermore, from the websites of the AFR100 (AFR100, n.d) and Initiative 20x20 (Initiative 20x20, n.d.), data was collected on which restoration projects are implemented. The AFR100 and Initiative 20x20 are regional initiatives related to the Bonn Challenge (Sewell et al., 2020), and thus provide information on the kind of NCS that government's restoration commitments result in.

Case studies on natural climate solutions

The article selection mentioned above was also used to select case studies that are useful to evaluate NCS. In addition to that the bibliography (University of Oxford, 2021) was scanned again, and supplemented with articles found via Scopus. In the end, 31 articles were found that analyse the implementation of an NCS and give information on its impact on at least one of the aspects climate change mitigation, biodiversity conservation, sustainable livelihoods, or other ecosystem services.

Data was also collected on the ecosystem in which the NCS was implemented. This was done through looking up geographical coordinates of the case in the article. If this was not available but only the place is described, coordinates of this place are looked up using Google Maps. After that, coordinates were plotted as points in ArcGIS against the terrestrial ecoregion map.

Results

In this chapter, the results are presented per research question.

RQ1: What natural climate solutions do governments commit to with the aim to reach emission- and restoration targets and do they lead to afforestation of non-forest ecosystems?

1.1 What commitments have governments made for tree planting and restoration of ecosystems?

Commitments in different ecosystems

The GRC database contains commitments in different restoration categories and ecosystems. In figure 3, the total commitments are given per continent in different ecosystems, relative to the total area of the continent. As can be seen, the restoration plans are not equally distributed across continents. Whereas in South Asia countries have made large commitments to restore and increase forest, in East Asia and the Pacific region the largest area is committed to improve soils in croplands. Besides that, the total area that was committed is larger in Global South regions Sub-Saharan Africa, South Asia and Latin America and the Caribbean, than in North America, Europe and Central Asia, and the Middle East and North Africa. East Asia and the Pacific, with China as main contributor, and the Middle East and North Africa, covered largely by deserts, are continents that differ from the others by only having a small part of their restoration commitments in the 'forest increase' and 'forest restoration' categories.

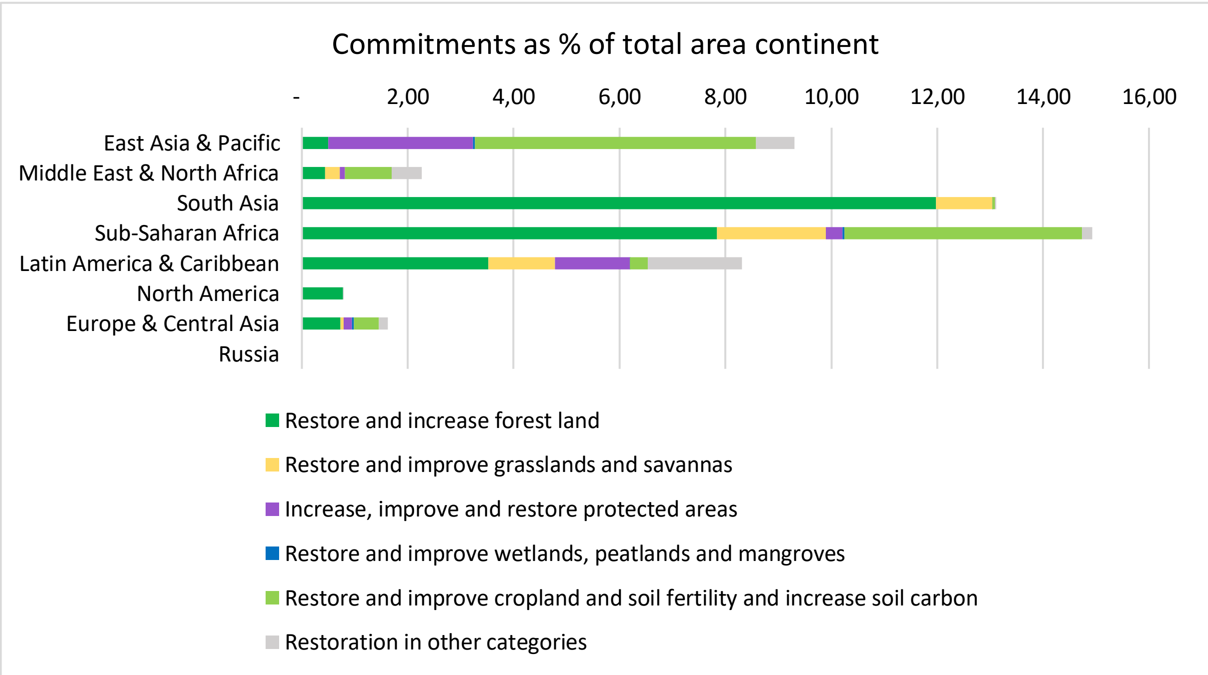

Figure 3: Restoration commitments in different categories per region, as a percentage of its total area

Forests restoration commitments compared to commitments for grassy biomes restoration

Of the restoration commitments, the combined commitments for 'forest restoration' and 'forest increase' are the largest. Eighty-four countries have made commitments of in total 2,827,645 km^2. This is 5,11 % of the total area in forest biomes on the WWF ecoregions map. Thirty-two countries made pledges for grassland restoration, a total of 565,887 km^2. This is 1,52% of the total area in grassy biomes on the WWF map.

Distribution of forest restoration commitments

To visualise the forest commitments geographically, the area committed compared to the total country area is presented in figure 4. The figure includes the forest commitments in the GCR database. Here, again, it is visible that countries in Latin America, South Asia and Sub-Saharan Africa have made relatively large commitments.

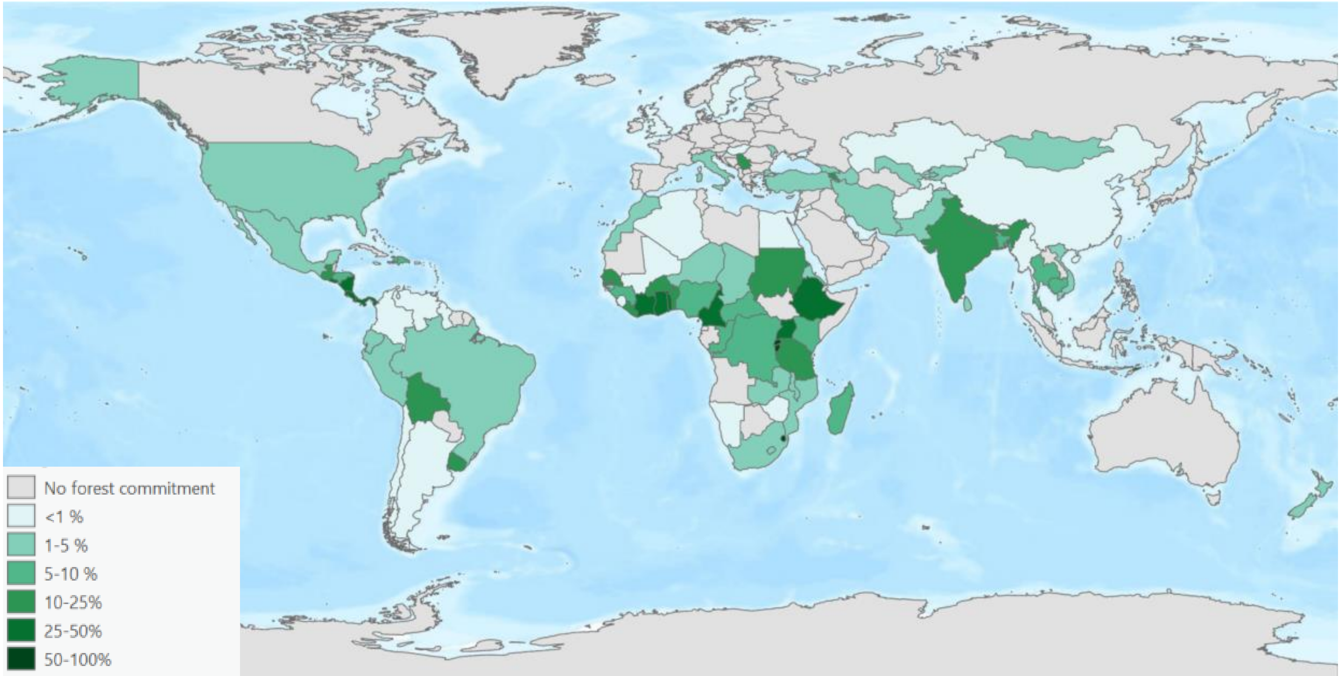

Figure 4: Quantitative commitments to increase or restore forest area per country, as a percentage of its total area

1.2 How do the forest commitments relate to the amount of land countries have available for forest restoration?

In figure 5, the forest commitments are plotted against the total area available in forest ecoregions per country. It should be mentioned that this is the total forest area available, without taking into account wild forests. There is no significant correlation between the variables 'forest land available' and 'forest commitments'. In the figure it can be seen that some of the countries with the largest area in forest ecosystems, including Russia and Canada , have not made quantitative forest commitments that are documented in the researched databases. Indonesia, another country with much forest area, also has a high national restoration target for forests. However this commitment is only shown in the FLR database and for Indonesia there are no forest restoration commitments in the larger PBL database. On the other hand, there are several countries that have relatively little forest area but have made large commitments, such as Ethiopia and Sudan. Many other Sub-Saharan African countries are also on the upper left side of the diagram, indicating that they have made large commitments relative to other countries, but little forest area. The majority of the European countries have not made commitments that are in the databases at all, although they are for largely covered by forest area. An exception is France, of which relatively large commitments for forest restoration were reported in the FLR database.

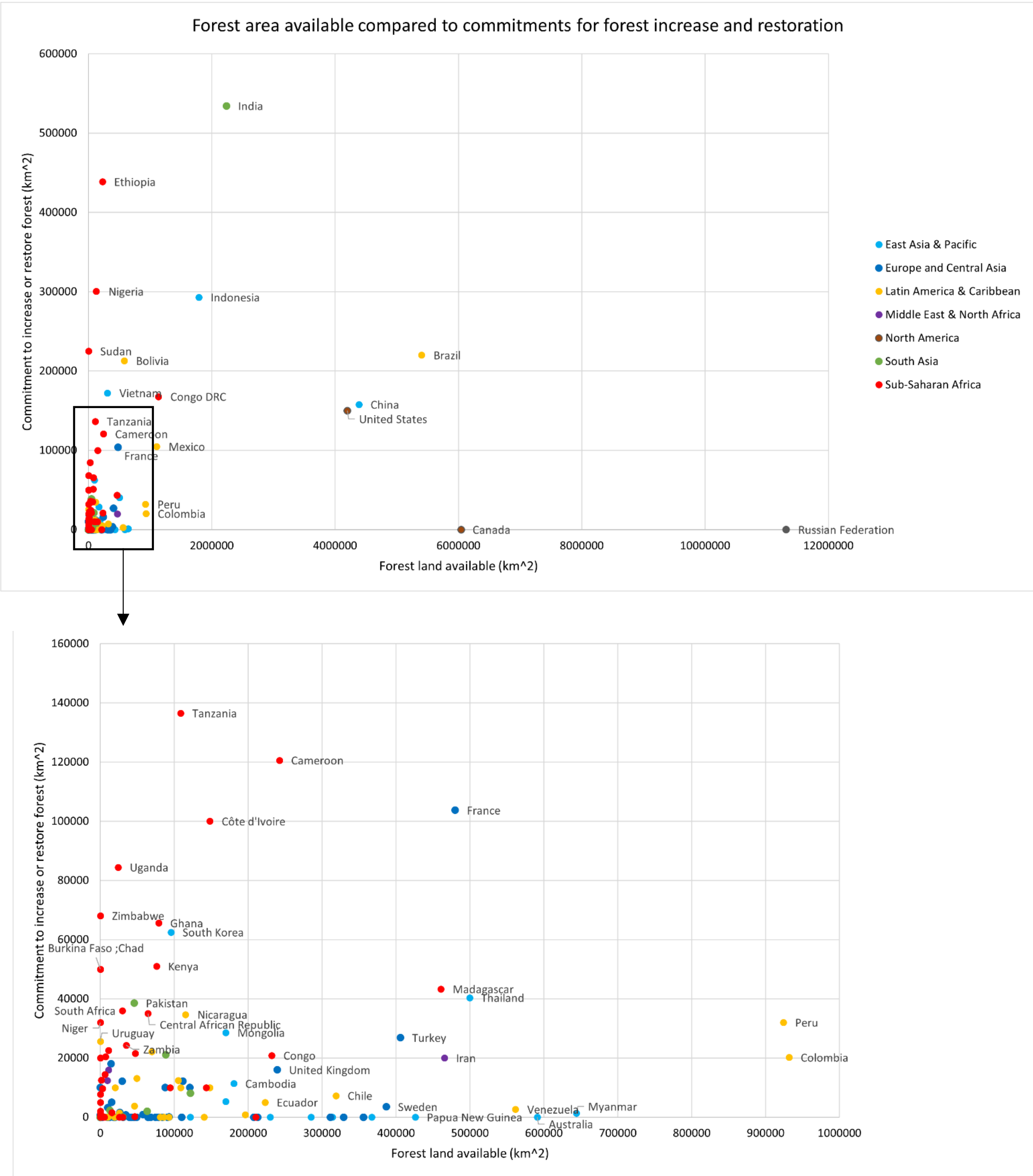

Figure 5: Forest area available compared to forest commitments made per country

Figure 6 shows the countries that have a surplus of forest commitments, compared to the area they have available for forest restoration. In 31 of the 98 countries, the commitments covered more area than the forest area available. The difference ranged from around 50 km^2 in some Middle Eastern countries to 222,324 km^2 in Sudan.

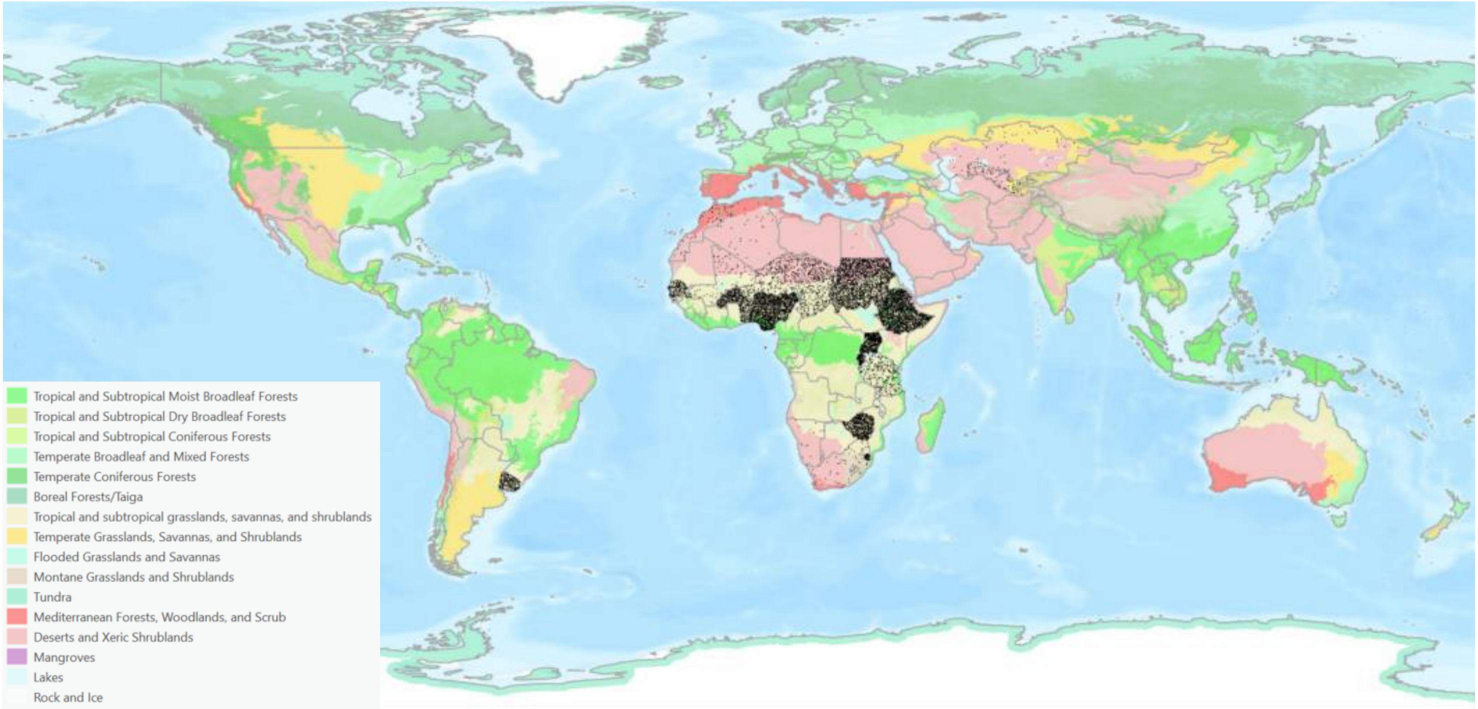

Figure 6: Countries that have committed to restore more forest than they have area available in forest ecoregions, filled with dots. Each black dot represents 100 km² commitment outside of forest ecoregions. On the background is the ecoregions (Olson et al., 2001) map.

Surplus forest commitments related to tropical grassy biomes
The countries with large surpluses are mainly countries in Sub-Saharan Africa. In addition to this, Uruguay also stands out, a country that is also completely covered by tropical and subtropical grassy biomes. In total, there is an area of 104.061.562 hectares surplus area of forest commitments where there is no forest area. The area committed to increase forest, that is outside of forest ecoregions, is covered by 71% in the ecoregion 'tropical and subtropical grasslands, savannas, and shrublands' on average. Globally, non-forest area is covered by 17% tropical grassy biomes. The data per country can be found in appendix 3.

Alternative distributions for forests and grassy biome
The same analysis as presented in figure 6, is done for the alternative distributions of grassy biomes and forests, in case all ecosystems uncertain would be forests, or all ecosystems uncertain would be grassy biomes (figure 7). The figure shows that in the case of maximum forest cover, only Egypt has a made a forest commitment that is larger than its area available for forest restoration. In the case of maximum cover of grassy biomes, 48 countries have made forest commitments larger than the land they have available for forest restoration. This includes countries that do not have a surplus of forest commitments in the basis scenario, for example some European countries, as well as India and Pakistan. The maps can be found in larger size in appendix 2.

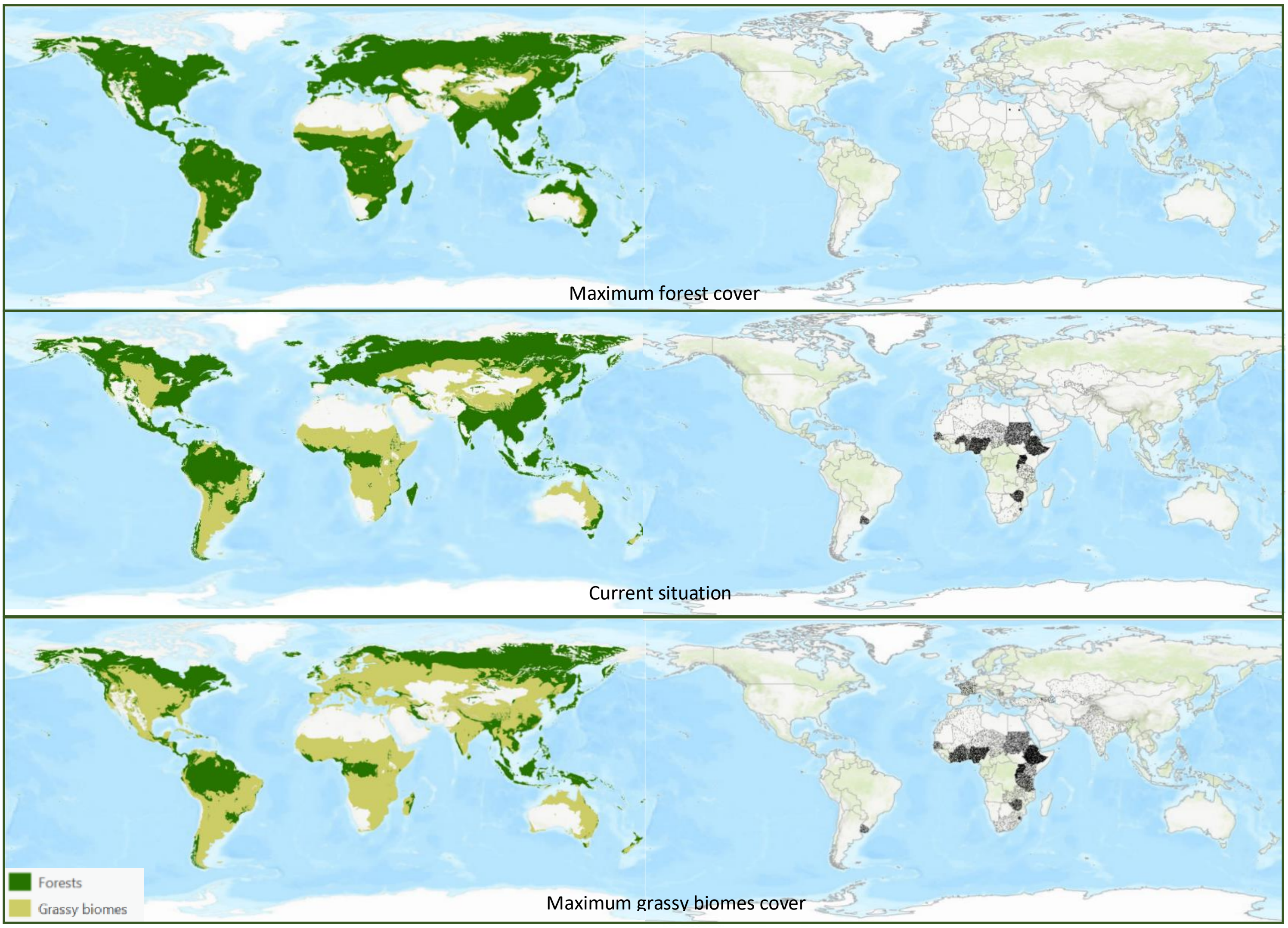

Figure 7: Alternative distributions of grasslands and forests (left) and the surplus countries would have committed to forest restoration (right), in case all ecosystems uncertain were forests (above) and in case all ecosystems uncertain would be grassy biomes (below). In the middle is the current situation for reference, that is also presented in figure 6.

Non-forest ecoregions described as deforested

Figure 8 demonstrates the percentage of each WWF ecoregion that is covered by 'deforested' or 'partially deforested' land according to the WRI Atlas that maps deforested areas. As can be seen, not only areas in forest ecoregions are classified as deforested, but also areas in other ecoregions. More than 25% of temperate grassy biomes and more than 40% of tropical and subtropical grassy biomes are described as deforested or partially deforested.

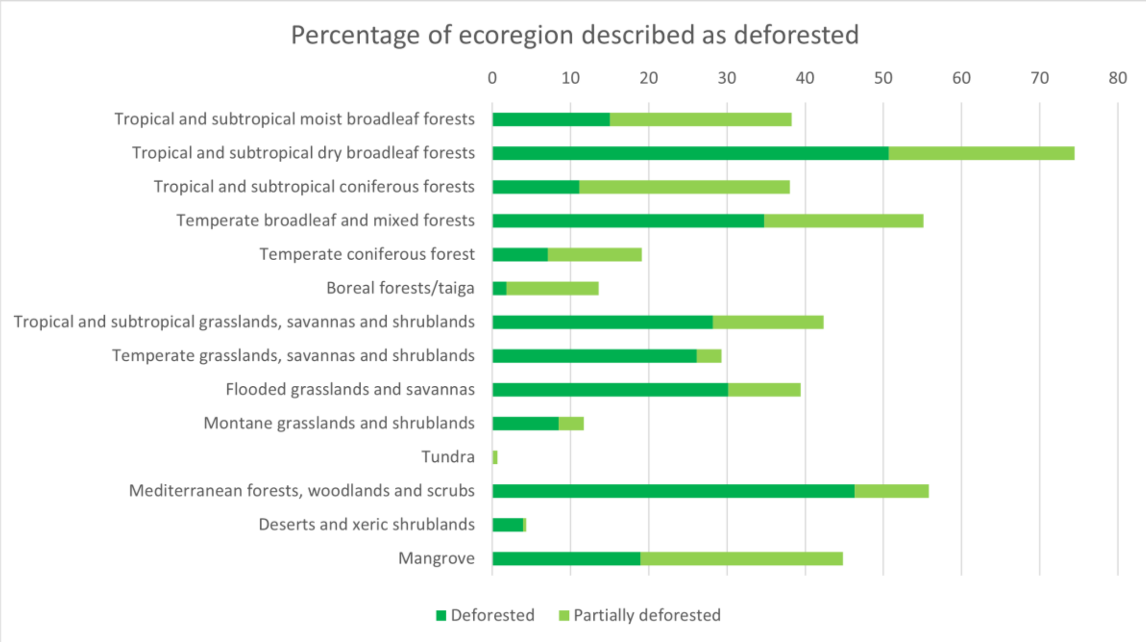

Figure 8: Percentage of each ecoregion that is categorised (partially) deforested by the Atlas of Forest Landscape Restoration Opportunities (WRI, 2014)

RQ2: What natural climate solutions beyond tree planting have potential to be implemented in the future for forest- and grassland ecosystems?

2.1 What solutions besides tree planting programs are currently proposed and to what extent are they already adopted or do they have potential to be implemented?

The inventory of implementation of restoration projects of the AFR100 and Initiative 20x20 is demonstrated in figure 9. The kind of NCS that the projects in these two initiatives were categorised in, are listed. These are projects that are already implemented.

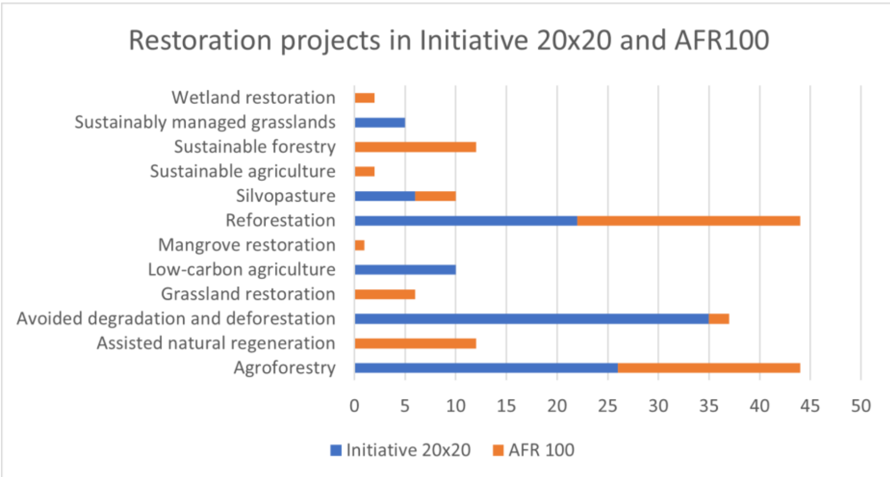

Figure 9: Restoration projects listed for the AFR 100 and Initiative 20x20

The proposed NCS from the seven articles that list NCS are presented in appendix 4. From those articles and the AFR100 and Initiative 20x20 projects, the six NCS below are selected to investigate on their estimated climate mitigation potential. They are interesting to study in the context of forest- and grassy biomes and are also listed in the AFR100 and Initiative 20x20.

- **Reforestation and grassland restoration:** These methods entail the restoration of the forest- and grassland ecosystems.
- **Natural regeneration:** Natural regeneration is restoration to a native ecosystem, but with no or little human intervention. It thus excludes methods such as tree planting. Methods in this category with some human intervention include farmer managed natural regeneration (Haglund et al., 2011) and assisted natural regeneration (Yang et al., 2018).

- **Avoided forest conversion and avoided grassland conversion:** These NCS do not involve restoration, but attempt to prevent degradation in the first place.
- **Fire management and grazing management:** Fire management and grazing management are interesting to study in the context of grasslands and forests, as fire and herbivores can determine whether a region is a forest or a grassland (Bond, 2005), either naturally or with the assistance of humans. Fire and grazers can be introduced in a combination, for example by using herbivores to reduce fuel for wildfires (Rouet-Leduc et al., 2021).
- **Agroforestry:** Agroforestry entails integrating trees in croplands (Wolz et al., 2018). It is a traditional method of agriculture in countries that are covered by tropical grassy biomes (Coulibaly et al., 2013).

Comparing climate mitigation potential

In table 2, the relative climate mitigation potential of the selected NCS is shown for different studies and different regions. As can be seen, the studies vary widely. The full table with the data used to calculate the percentages can be found in appendix 5.

NCS	Griscom et al., 2017 (Global)	Griscom et al., 2020 (Tropical regions)	Fargione et al., 2018 (United States)	Drever et al., 2021 (Canada)
Reforestation	42.63%	17.85%	25.50%	<0.1%
Grassland restoration	-	-	0.75%	-
Agroforestry	2.59%	14.24%	6.81%	5.02%
Natural regeneration	0.93%	-	-	-
Avoided forest conversion	15.17%	43.25%	3.16%	4.89%
Avoided grassland conversion	0.49%	-	8.89%	16.34%
Grazing management	4.95%	0.42%	0.91%	-
Fire management	0.89%	26.87%	1.50%	-
Other	32.35%	24.23%	52.48%	73.75%
Total (absolute)	23750 $TgCO^2eyr^{-1}$	6535.4 $TgCO^2eyr^{-1}$	1203.7 $TgCO^2eyr^{-1}$	77.7 $TgCO^2eyr^{-1}$

Table 2: Relative climate mitigation potential of NCS according to different studies

2.2 To what extent do these solutions facilitate synergies with conserving biodiversity and providing ecosystem services to local livelihoods?

The 31 case studies that were found to evaluate the implementation of a single NCS and its impact on climate mitigation, biodiversity conservation, or livelihoods, are summarised in table 3. Impacts on other ecosystem services, such as water provision, were also noted down. For each of the case studies, the table demonstrates if the impact on the criteria was positive, negative, or not reported. The full table, containing more information, can be found in appendix 6. It should be noted that some case studies were theoretical and not based on empirical results. This applies for example to the study by Pires et al. (2017) that models the impacts of reforestation on a specific region in Brazil and argues it will be beneficial to all aspects. Besides that, the articles differ in level of detail. Whereas some are very specific, and report for example 'a 1.7% increase in SOC' (Zhang et al., 2017), others simply describe 'benefits for biodiversity' (Russel-Smith et al., 2015). Sometimes the impact is demonstrated as 'neutral'. This means it was mentioned, but neither positive nor negative. In some of these cases both negative and positive impacts were described, in other only one effect was described but this was not negative or positive. For example, several times it was mentioned, 'vegetation increased', but it was not clear if this was native vegetation and if species diversity increased. Thus, the impact on biodiversity is classified as neutral. As is demonstrated in the table, the vast majority of the cases are in the category of reforestation and afforestation. Only in these categories, negative impacts have been found. Most of the case studies do not cover all three dimensions. For agroforestry, two cases were found that described positive impacts in all categories. No case studies were found for grazing management. Concerning the ecosystem services besides carbon sequestration and biodiversity conservation, mostly impacts on soil and water were described.

NCS	**Article**	Climate mitigation	Biodiversity conservation	Livelihoods	Other ecosystem services	**Forest or grassy biome**
Reforestation	Warner et al., 2021	Negative	Neutral	Not reported	Not reported	Forest
	Scheidel & Work, 2018	Neutral	Negative	Negative	Not reported	Forest
	Lin et al., 2012	Neutral	Neutral	Positive	Positive	Forest
	Pires et al., 2017*	Positive	Positive	Positive	Positive	Forest
	Hani et al., 2017	Not reported	Neutral	Positive	Neutral	Other
	Schirone et al., 2011	Not reported	Positive	Not reported	Not reported	Other
	McElwee et al., 2017	Not reported	Not reported	Negative	Not reported	Forest
	Rana & Miller, 2021	Not reported	Neutral	Neutral	Not reported	Mix/unclear
	Wheeler et al., 2016	Positive	Positive	Not reported	Not reported	Other
Afforestation	Lan et al., 2021	Neutral	Not reported	Not reported	Negative	Grassy biome
	Ullah et al., 2021	Not reported	Neutral	Neutral	Neutral	Mix/unclear
	Hajdu et al., 2016	Not reported	Not reported	Negative	Not reported	Grassy biome
	Ramprasad et al., 2020	Not reported	Neutral	Negative	Not reported	Mix/unclear
	Jiao et al., 2010	Not reported	Neutral	Not reported	Neutral	Mix/unclear
Agroforestry	Khan et al., 2017	Not reported	Not reported	Not reported	Positive	Other
	Fadina & Barjolle, 2018	Positive	Positive	Positive	Positive	Grassy biome
	Costa et al., 2018	Positive	Positive	Positive	Positive	Grassy biome
	Pandit et al., 2019	Not reported	Not reported	Not reported	Positive	Mix/unclear
Natural regeneration (including FMNR)	Belem et al., 2017	Not reported	Positive	Positive	Not reported	Grassy biome
	Salete Capellesso et al., 2021	Positive	Positive	Not reported	Not reported	Forest
	Haglund et al., 2011	Not reported	Neutral	Positive	Not reported	Grassy biome
Conservation agriculture	Lalani et al., 2018	Not reported	Not reported	Positive	Positive	Grassy biome
	Chan et al., 2017	Not reported	Not reported	Positive	Positive	Forest
Fire management	Wiedinmyer & Hurteau, 2010*	Positive	Neutral	Not reported	Not reported	Mix/unclear
	Russel-Smith et al., 2015	Positive	Positive	Positive	Positive	Grassy biome
Grassland restoration	Huang et al., 2014	Positive	Positive	Not reported	Not reported	Grassy biome
	Zhang et al., 2017	Positive	Not reported	Not reported	Not reported	Grassy biome
Silvopasture	Andrade et al., 2009	Positive	Not reported	Not reported	Not reported	Forest
Other restoration	Sarma et al., 2013*	Positive	Not reported	Not reported	Not reported	Forest
	Bourne et al., 2017	Not reported	Neutral	Not reported	Not reported	Other
	Schmiedel et al., 2017	Positive	Positive	Not reported	Positive	Other

*These are theoretical case studies, not based on empirical results

Legend

Green	Positive impact	Thermometer	Climate mitigation
Red	Negative impact	Leaf	Biodiversity conservation
Blue	Neutral	People	Livelihoods
Grey	Not reported	Drop	Other ecosystem services

Table 3: Outcome of the literature study on NCS' impact on climate mitigation, biodiversity conservation and livelihoods

Discussion

As expected, the number of countries that committed to forest restoration as well as the total area pledged is much larger than is the case for grassland restoration. It should be noted that some countries, particularly China and countries in Sub-Saharan Africa, have made substantial commitments in the category 'restore and improve cropland and soil fertility and increase soil carbon'. The natural ecosystem is not specified and can thus refer to forests, grassy biomes or other ecosystems. Similarly, grasslands and agriculture are combined in some literature including the research by Griscom et al. (2017). They describe 'agriculture and grasslands' as one category, next to 'forests' and 'wetlands'.

From the comparison of the forest commitments to the amount of land in forest ecoregions, Sub-Saharan African countries on the left side of the scatterplot stand out. They made relatively large commitments for forest increase and restoration, but have relatively low or no area in forest ecoregions. This is in line with the literature (Bond et al., 2019). From the five countries in the world that possess more than halve of the world's forest, Russia, Brazil, Canada, the United States and China (FAO, 2020), some have made large forest commitments, but some have made none that are registered in the databases. When calculating a correlation coefficient between forest land and forest commitments, there is no significant correlation. This is opposed to the hypothesis that states countries with more forest land would have made larger commitments to restore forests.

The surplus of commitments when subtracting the land available for forest restoration is, as expected, largely situated in the tropical grassy biomes of Sub-Saharan Africa. The results show in total more than 100 million hectares have been committed to forest increase where the ecosystem, according to the WWF terrestrial ecosystem mapping is not a forest. Clearly, the countries in which this area situated, are covered by more tropical grassy biomes than the average country.

As described at the start of this report, it is claimed one of the reasons for forest restoration projects to be planned in non-forest ecosystems is falsely describing ecosystems with a natural low tree cover as deforested. The analysis in this research of the shows the Atlas of Forest Landscape Restoration Opportunities (WRI, 2014) does indeed classify not only forests as 'deforested' or 'partially deforested', but also other ecoregions. More than 40% of tropical and subtropical grassy biomes is classified such. Veldman et al. (2015b), performed a similar analysis, comparing the world's ecoregions to the restoration allocation of the Atlas. They found 9 million square kilometers of grassy biomes to be classified suitable for 'wide-scale' or 'mosaic restoration'. The debate of when of when an ecosystem is degraded knows many perspectives on how degradation should be defined, and researchers are still developing new arguments (Hobbs, 2016). Hajdu et al. (2016) show how this applies to the definition of deforestation, that they argue is misused by forestry companies and should be scrutinised more closely. Besides misusing deforestation as justification for forestry projects, scientists also argue degradation mapping should not solely rely on using tree cover as an indicator. Scientists show grassy biomes are not only distinct by low tree cover, but also unique in species composition (Fayolle et al., 2018; Aleman et al., 2020). Joshi et al. (2018) describe how wrongly perceiving grasslands in the Global South has been occurring for centuries. They describe how ancient grasslands in India in the 19th century were selected for plantations by colonialists, who believed the grasslands were shaped by forest destruction as a consequence of intensive land use, and draw parallels with today's studies that model reforestation opportunities.
When looking at the alternative distributions for grasslands and forests using the ecosystems uncertain concept, the difference between the forest commitments and forest land shows an interesting result. In the case of maximum forest cover, only one of the countries has committed more it have forest land, compared to 33 countries in the original scenario. This could indicate that, indeed, countries make commitments for forest increase according to the possibilities of

climate, rather than the native ecosystem. In the case that has the least forest area and the maximum expansion of grassy biomes, 48 countries have made commitments that would be realised outside of forest land. It demonstrates which countries, in addition to the countries that are identified in the original scenario, could possibly afforest grasslands. After all, the terrestrial ecoregions map misses out on some native grasslands (Veldman et al., 2015b)

The literature research reveals a variety of natural climate solutions for forests and grassy biomes. Surprisingly, the modelled ability per solution to sequester carbon varies widely between studies. Partially, the difference between the studies can be explained by their different geographical focus, still the differences are large. Whereas the studies by Griscom et al. (2017) and Fargione et al. (2018) attribute a large part of the climate mitigation potential to reforestation (42.63% and 25.50%, respectively), Drever et al. (2021) only estimate it to be less than 0.1 percent. Grassland restoration is represented to a much smaller extent, only being mentioned with this exact definition by Fargione et al. (2018) and estimated to cover 0.75% of the NCS's climate mitigation potential. The climate mitigation potential of other NCS that can be relevant for grasslands, grazing management and fire management also show large differences between the studies, with the newest Griscom et al. (2020) study attributing a relatively large portion of 26.87% to it. Surprising is the low climate mitigation potential share of avoided forest conversion. Three of the four studies estimate its sequestration potential to be smaller than reforestation. The same applies to natural regeneration, that is only mentioned by the first Griscom et al. (2017) study and represents a small percentage of the mitigation potential.
In short, the results of the review are in line with the expectation that points to a bias towards forest ecosystems, but at odds with the literature that shows avoiding degradation of intact ecosystems natural regeneration are the most effective measures for reducing greenhouse gas concentrations.

The NCS that are represented most in the case studies are reforestation and afforestation. The number of case studies located in grassy biomes is comparable to the number of case studies located in forest ecosystems. Still, most describe NCS specifically for forests. This is in line with the expectation that there is still less research and implementation of NCS for grassy biomes. As expected, the afforestation and reforestation cases, that are associated with tree planting, describe more negative impacts than the other solutions. Chausson et al. (2020), that also contributed the bibliography that was used, also argue that created ecosystems more often involve trade-offs. A synergy between climate mitigation, biodiversity conservation and sustainable livelihoods is found in two agroforestry case studies. Agroforestry is a broad NCS, that is listed in the literature under different methods, such as 'windbreaks' and 'trees in agricultural landscapes' (Appendix 4). Interestingly, it is a solution that comes from local farmers (Coulibaly et al., 2013), that have already been using it with native vegetation. Some researchers (Hosen et al., 2020) argue traditional knowledge could particularly bring effective natural solutions. Besides agroforestry, other NCS represented in the case studies, namely natural regeneration, conservation agriculture and fire management also show to have positive effects on at least two of the aspects and report no negative effects.

Limitations

There are several limitations to this research. First of all, the values for both the forest land per country and the forest commitment are not optimal. Although the WWF terrestrial ecoregions map is used by many, even this map is argued to be not completely correct on the balance between forests and grassy biomes. Veldman et al. (2015) and Parr et al. (2014) show areas that have been mapped as forests are in fact ancient grassy biomes. Furthermore, the assumption that a surplus of forest restoration commitment compared to the area available for forest restoration leads to afforestation, likely represents reality to a very limited extent. The commitments are only plans, of which it is unsure if they will be implemented. Besides that, even

if the commitments would be implemented exactly as they are, the calculations in this research only reveal countries that cannot realise the forest restoration commitments due to a shortage of forest land. It is possible that other countries will also afforest other ecosystems, but this does not become clear because they also have a lot of forest land. In short, the calculation is simple and does not give an exact indication of in which ecosystems countries plan to realise commitments for forest increase.
Regarding the second research question, the case study review can miss out on practices that are not described as natural climate solutions, but are still relevant and even fall into one of the presented NCS such as fire management or conservation agriculture, as these solutions have existed long before the concept of NCS.

Conclusions

This research provides insights into the relation between ecosystem restoration commitments, natural climate solutions, land in grassy biomes and forest ecosystems, and the synergy of tackling climate change with solutions that have positive impacts on people and nature.
Commitments to restore ecosystems in order to reach targets differ largely per country and per continent. The difference cannot be explained by the amount of forest land each country has available for restoration. Some countries have even made commitments larger than is possible according to the land they have in forest ecoregions. Many of these countries are situated in Sub-Saharan Africa and are covered largely by tropical grassy biomes.
Articles comparing the effectiveness of NCS differ largely in estimates, in which, as expected, NCS for grassy biomes do not have a large share in the climate mitigation potential.
Reforestation and afforestation dominate the literature studied on natural climate solutions. Other possible natural climate solutions for grassy biomes and forest ecosystems include natural regeneration, fire management, grazing management and agroforestry. All of these solutions can be found in case studies that report positive impacts on at least two of the aspects 'climate change mitigation', 'biodiversity conservation', and 'sustainable livelihoods'.

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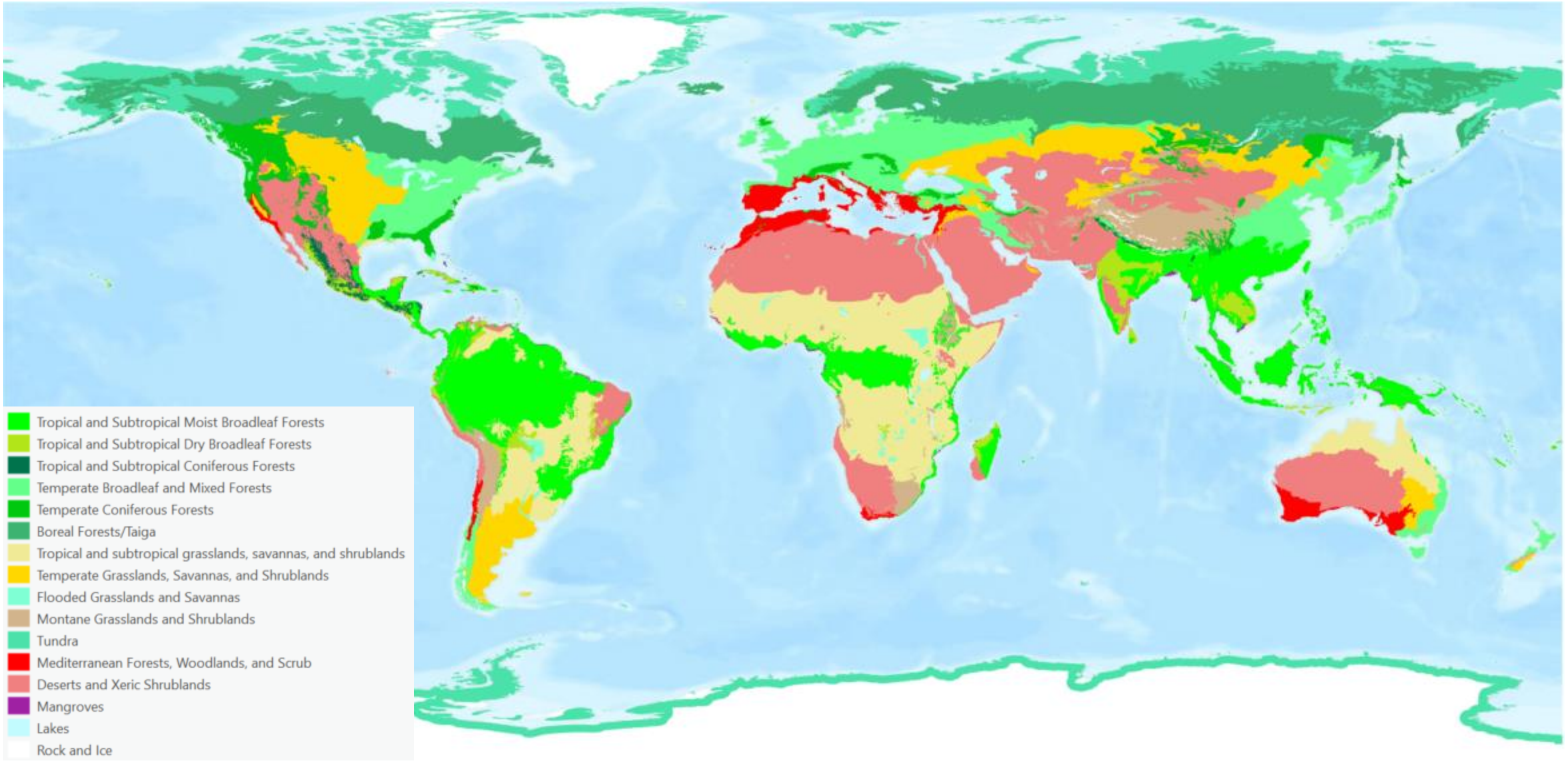
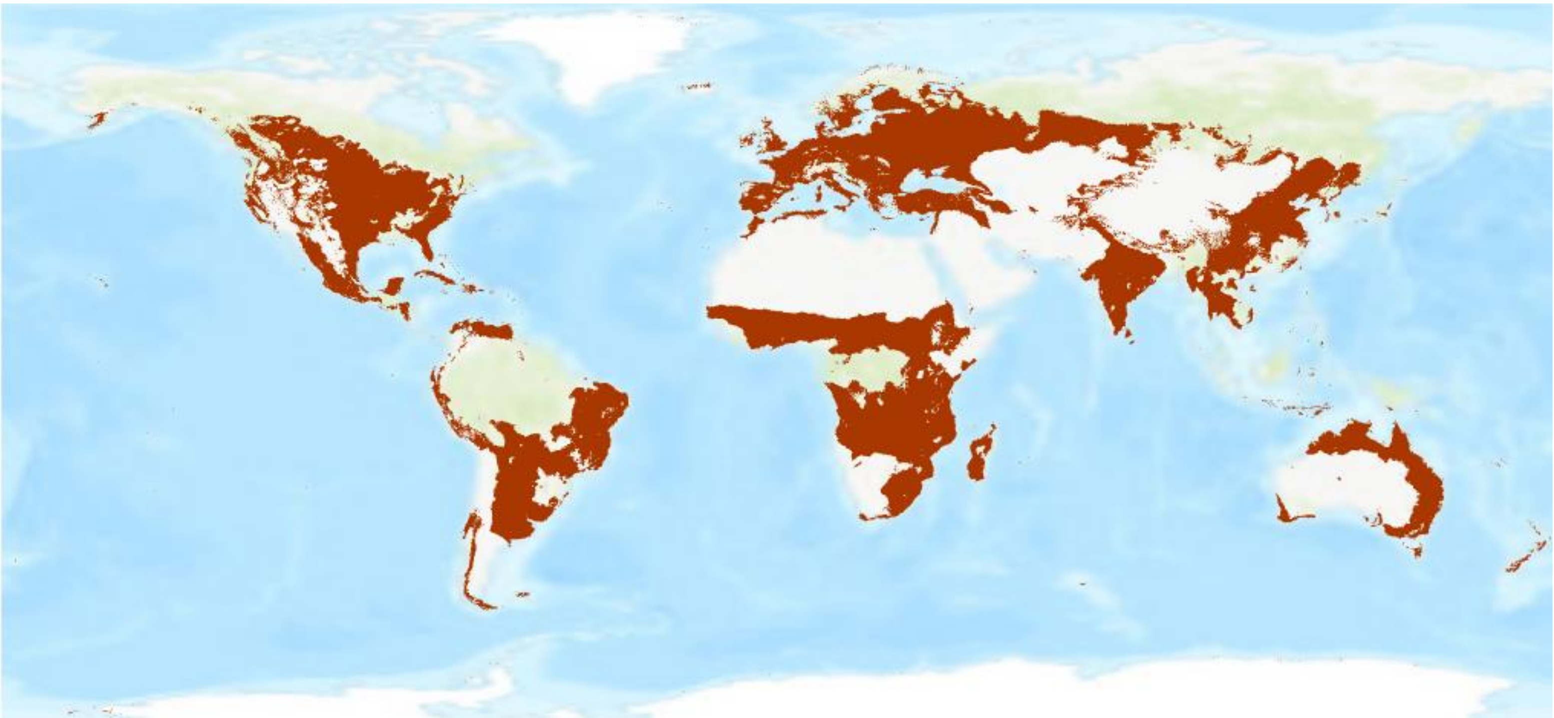
Appendix 1: Input maps

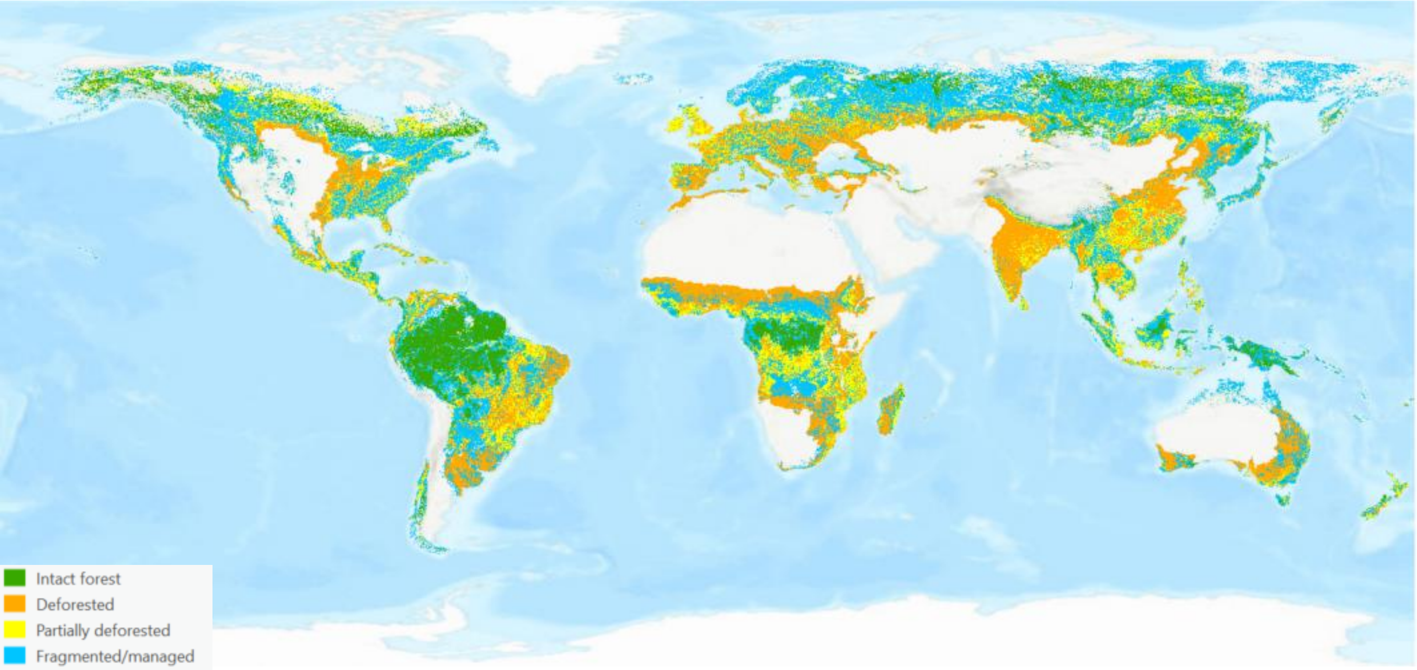
WWF terrestrial ecoregions (Olson et al., 2001)



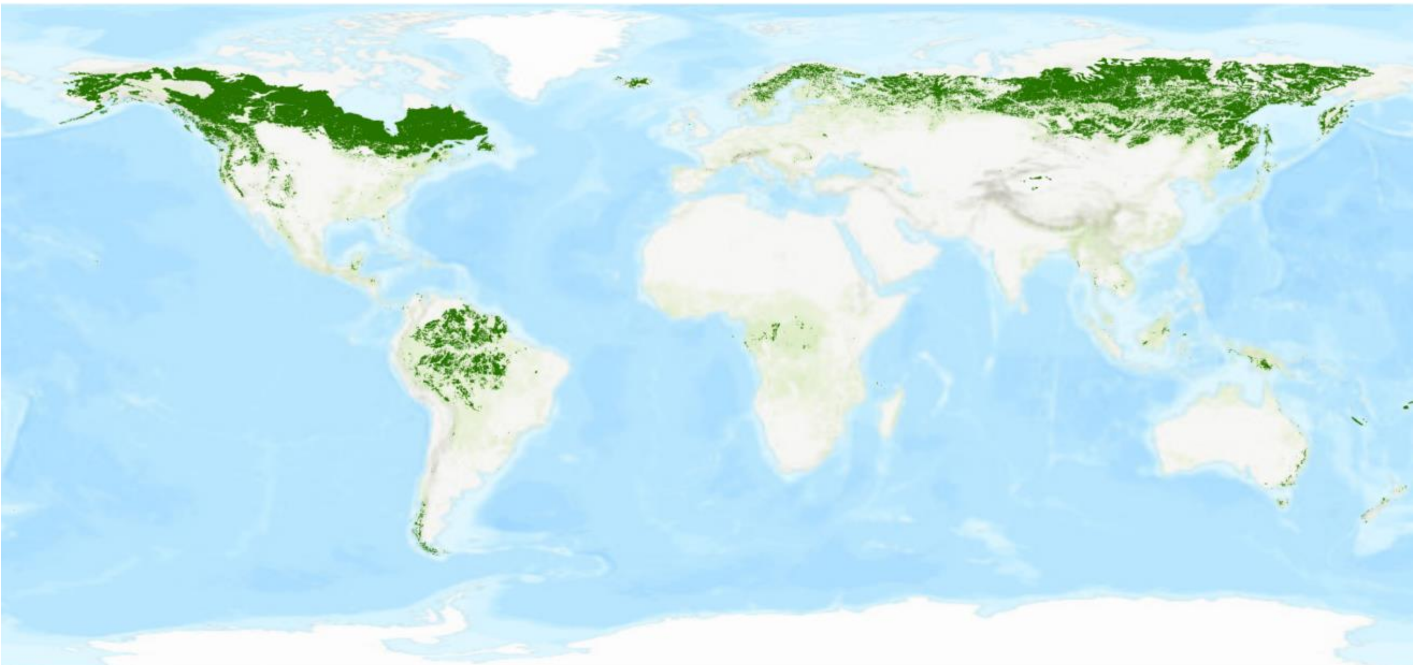
Ecosystems uncertain (Bond, 2005)



Atlas of Forest Landscape Restoration Opportunities (WRI, 2014)

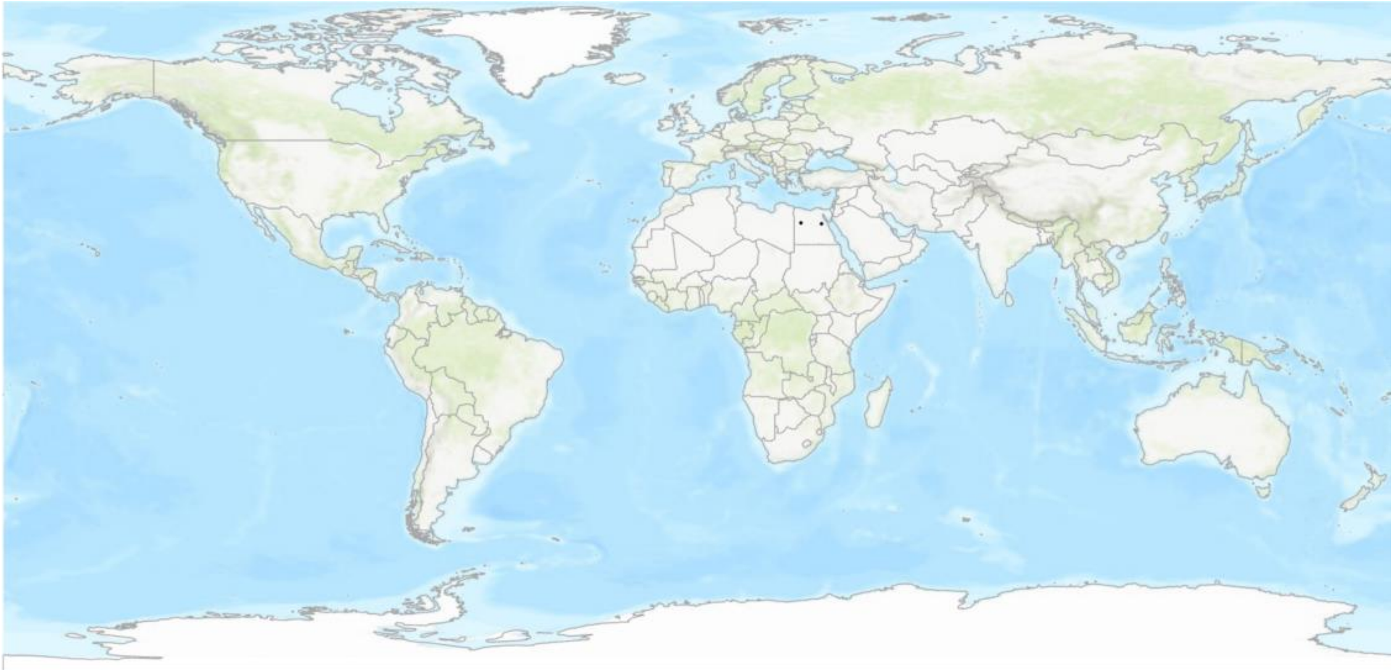


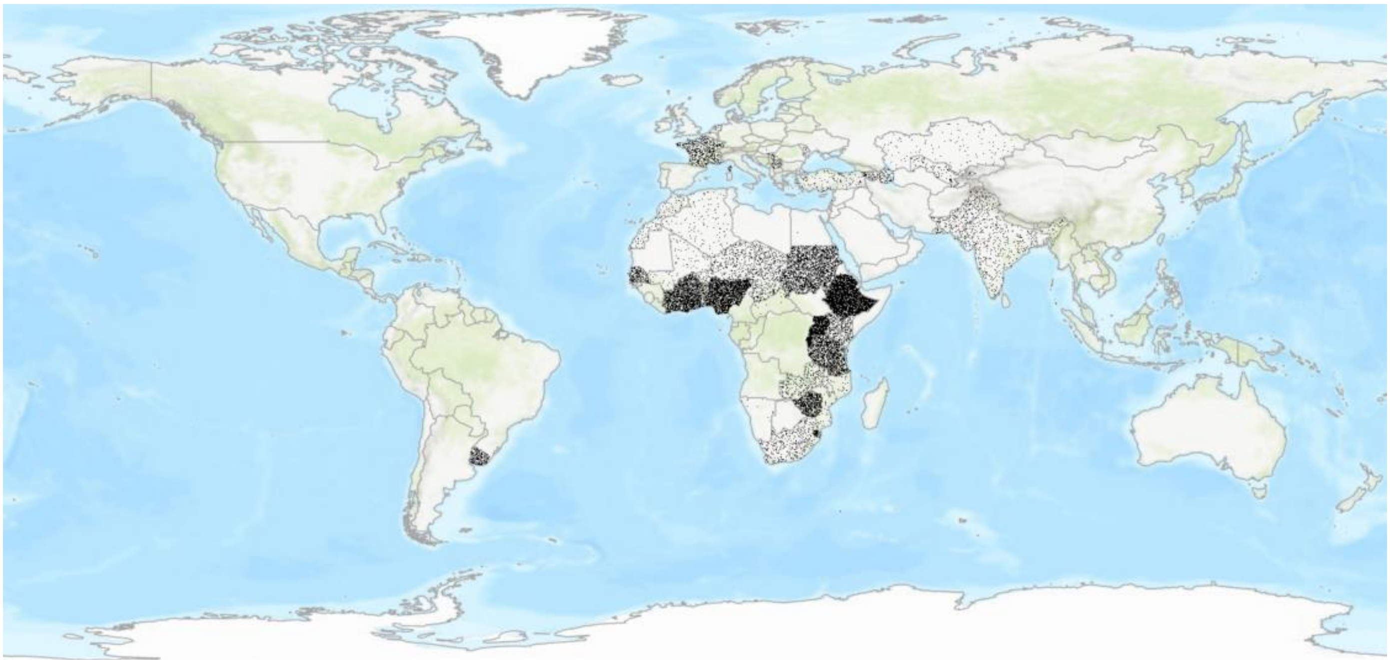
Intact forests, defined by wild anthromes (Klein Goldewijk et al., 2017) in forest ecoregions (Olson et al., 2001)



Appendix 2: Large maps of results

Enlarged maps of figure 7





Appendix 3: Country overview

Area unit = km^2

Country	Total area (km²)	Continent (Worldbank, 2018)	Forest ecoregions (km²)	Wild forests (km²)	Forest commitment PBL (middle estimate 1) (km²)	FLR commitment (km²)	Forest land available for restoration – total forest commitment (km²)	TGBs (km²)
Afghanistan	641908	South Asia	12920	0	2321	0	10599	0
Albania	28654	Europe & Central Asia	2498	0	0	0	2498	0
Algeria	2317510	Middle East & North Africa	9417	0	12450	0	-3033	0
American Samoa	164	East Asia & Pacific	125	106	0	0	19	0
Andorra	507	Europe & Central Asia	507	0	0	0	507	0
Angola	1247368	Sub-Saharan Africa	5459	0	0	0	5459	1082538
Antigua and Barbuda	537	Latin America & Caribbean	101	0	0	0	101	0
Argentina	2780991	Latin America & Caribbean	148188	12532	10000	0	125656	651951
Armenia	29669	Europe & Central Asia	15378	0	5000	0	10378	0
Aruba	200	Latin America & Caribbean	0	0	0	0	0	0
Australia	7686939	East Asia & Pacific	591010	45317	0	0	545693	2124490
Austria	83946	Europe & Central Asia	83946	710	0	0	83236	0
Azerbaijan	164317	Europe & Central Asia	29622	1	2700	12180	17441	0
Bahamas	12137	Latin America & Caribbean	5336	307	0	0	5029	0
Bahrain	640	Middle East & North Africa	0	0	0	0	0	0
Bangladesh	137879	South Asia	121825	0	8100	1400	113725	121
Barbados	446	Latin America & Caribbean	0	0	0	0	0	0
Belarus	207721	Europe & Central Asia	207721	1656	0	0	206065	0
Belgium	30652	Europe & Central Asia	30626	0	0	0	30626	0
Belize	22093	Latin America & Caribbean	19331	391	0	0	18939	0
Benin	116184	Sub-Saharan Africa	1486	0	12550	0	-11064	114600

Bermuda	21	North America	19	0	0	0	19	0
Bhutan	39837	South Asia	30464	439	25	0	30001	139
Bolivia	1086609	Latin America & Caribbean	578764	105852	213000	0	259912	254805
Bosnia and Herzegovina	51527	Europe & Central Asia	46500	0	0	0	46500	0
Botswana	578339	Sub-Saharan Africa	0	0	0	0	0	310255
Brazil	8472307	Latin America & Caribbean	5402325	1403683	220000	32000	3778642	2174413
British Virgin Islands	115	Latin America & Caribbean	17	0	0	0	17	0
Brunei Darussalam	5747	East Asia & Pacific	5602	671	0	0	4930	0
Bulgaria	111023	Europe & Central Asia	110220	254	0	0	109966	0
Burkina Faso	272341	Sub-Saharan Africa	0	0	50000	11950	-50000	272341
Burundi	27186	Sub-Saharan Africa	6938	2	20383	0	-13447	18441
Cabo Verde	4031	Sub-Saharan Africa	3645	3	200	0	3442	0
Cambodia	181742	East Asia & Pacific	180680	4583	11342	0	164755	0
Cameroon	464756	Sub-Saharan Africa	242448	24	120600	0	121824	214992
Canada	9953045	North America	6043343	5048003	0	0	995341	0
Cayman Islands	209	Latin America & Caribbean	57	0	0	0	57	0
Central African Republic	618643	Sub-Saharan Africa	64470	650	35000	0	28821	554172
Chad	1271847	Sub-Saharan Africa	0	0	50000	0	-50000	740839
Chile	744392	Latin America & Caribbean	318826	55167	7260	6000	256398	0
China	9405600	East Asia & Pacific	4384361	56992	21000	157717	4169652	0
Christmas Island	124	East Asia & Pacific	115	0	0	0	115	0
Cocos Islands	18	East Asia & Pacific	9	0	0	0	9	0
Colombia	1135172	Latin America & Caribbean	931739	156032	10220	20180	755527	152690
Comoros	1716	Sub-Saharan Africa	1603	1524	0	0	79	0
Congo	344024	Sub-Saharan Africa	232029	38916	20844	10010	172269	111922
Congo DRC	2326623	Sub-Saharan Africa	1135009	13780	160000	167758	953471	1171079
Cook Islands	151	East Asia & Pacific	127	0	0	0	127	0
Costa Rica	51078	Latin America & Caribbean	49306	0	13076	2343	36230	0
Côte d'Ivoire	321326	Sub-Saharan Africa	148271	0	100000	0	48271	172412
Croatia	55889	Europe & Central Asia	42090	60	0	0	42029	0

Cuba	109205	Latin America & Caribbean	92629	12	0	0	92616	0
Curacao	473	Latin America & Caribbean	0	0	0	0	0	0
Cyprus	9137	Europe & Central Asia	0	0	0	0	0	0
Czech Republic	78755	Europe & Central Asia	78755	55	0	0	78700	0
Denmark	42711	Europe & Central Asia	39456	96	0	0	39360	0
Djibouti	21435	Middle East & North Africa	0	0	0	0	0	0
Dominica	770	Latin America & Caribbean	567	0	0	0	567	0
Dominican Republic	48368	Latin America & Caribbean	46199	0	3820	0	42379	0
Ecuador	255309	Latin America & Caribbean	222891	1008	5000	0	216884	0
Egypt	998412	Middle East & North Africa	12	0	183	0	-170	0
El Salvador	20570	Latin America & Caribbean	19989	2	10000	10000	9987	0
Equatorial Guinea	26922	Sub-Saharan Africa	25876	0	0	0	25876	0
Eritrea	120904	Sub-Saharan Africa	15622	0	1589	0	14033	55342
Estonia	45933	Europe & Central Asia	44589	529	0	0	44060	0
Eswatini	17110	Sub-Saharan Africa	2947	0	9704	0	-6757	6986
Ethiopia	1127548	Sub-Saharan Africa	227266	85	438605	143022	-211423	572878
Falkland Islands	11493	Latin America & Caribbean	0	0	0	0	0	0
Faroe Islands	1484	Europe & Central Asia	0	0	0	0	0	0
Fiji	18074	East Asia & Pacific	16750	16273	0	0	477	0
Finland	335281	Europe & Central Asia	329256	79107	0	0	250149	0
France	548055	Europe & Central Asia	480084	1049	0	103712	375323	0
French Guiana	83594	Latin America & Caribbean	81139	44337	0	0	36802	0
French Polynesia	2083	East Asia & Pacific	1745	0	0	0	1745	0
Gabon	260693	Sub-Saharan Africa	210360	8809	0	0	201551	45000
Gambia	10723	Sub-Saharan Africa	0	0	4988	0	-4988	9687
Georgia	69957	Europe & Central Asia	57531	597	900	525	56034	0
Germany	357221	Europe & Central Asia	355886	463	0	0	355423	0
Ghana	239039	Sub-Saharan Africa	79125	0	65580	16672	13545	157730
Gibraltar	8	Europe & Central Asia	0	0	0	0	0	0
Greece	130066	Europe & Central Asia	12575	129	0	0	12446	0

Greenland	2159852	Europe & Central Asia	0	0	0	0	0	0
Grenada	346	Latin America & Caribbean	285	0	1	0	284	0
Guadeloupe	1652	Latin America & Caribbean	707	0	0	0	707	0
Guam	576	East Asia & Pacific	521	0	0	0	521	0
Guatemala	109023	Latin America & Caribbean	105237	4049	12400	8250	88788	0
Guinea	245053	Sub-Saharan Africa	47452	0	21500	0	25952	194346
Guinea-Bissau	33257	Sub-Saharan Africa	0	0	400	0	-400	24064
Guyana	210586	Latin America & Caribbean	196213	83647	802	0	111764	13467
Haiti	27171	Latin America & Caribbean	25833	0	1480	0	24353	0
Heard Island and McDonald Islands	400	East Asia & Pacific	0	0	0	0	0	0
Honduras	112214	Latin America & Caribbean	108801	2296	10000	0	96505	0
Hungary	92995	Europe & Central Asia	92995	58	50	0	92887	0
Iceland	102952	Europe & Central Asia	90895	36663	0	0	54232	0
India	3152151	South Asia	2236354	298	534333	104000	1701724	11612
Indonesia	1878881	East Asia & Pacific	1790643	42763	0	292950	1454931	8044
Iran	1678344	Middle East & North Africa	465655	918	20000	0	444738	0
Iraq	436272	Middle East & North Africa	30372	0	0	0	30372	0
Ireland	69637	Europe & Central Asia	68223	111	0	0	68112	0
Israel	20720	Middle East & North Africa	0	0	0	0	0	0
Italy	300077	Europe & Central Asia	111512	1604	12200	0	97708	0
Jamaica	11037	Latin America & Caribbean	10446	0	0	0	10446	0
Japan	371207	East Asia & Pacific	367123	12372	0	0	354751	0
Jordan	89215	Middle East & North Africa	0	0	50	0	-50	0
Kazakhstan	2842209	Europe & Central Asia	14642	1781	18000	0	-5139	0
Kenya	581864	Sub-Saharan Africa	76079	592	51000	42100	24487	394549
Kiribati	423	East Asia & Pacific	0	0	0	0	0	0
Kuwait	16740	Middle East & North Africa	0	0	0	0	0	0
Kyrgyzstan	199565	Europe & Central Asia	10177	466	3232	0	6479	0
Laos	229885	East Asia & Pacific	229885	1423	0	0	228462	0

Latvia	64643	Europe & Central Asia	64537	188	0	0	64350	0
Lebanon	10214	Middle East & North Africa	0	0	100	0	-100	0
Lesotho	30516	Sub-Saharan Africa	0	0	613	0	-613	0
Liberia	96004	Sub-Saharan Africa	94325	0	10000	0	84325	118
Libya	1617580	Middle East & North Africa	0	0	0	0	0	0
Liechtenstein	176	Europe & Central Asia	176	0	0	0	176	0
Lithuania	65011	Europe & Central Asia	64948	130	0	0	64818	0
Luxembourg	2581	Europe & Central Asia	2581	0	0	0	2581	0
Madagascar	592996	Sub-Saharan Africa	460780	548	43300	0	416932	0
Malawi	118487	Sub-Saharan Africa	68	0	2012	0	-1944	71222
Malaysia	328499	East Asia & Pacific	313882	464	0	0	313419	0
Maldives	34	South Asia	30	0	0	0	30	0
Mali	1252295	Sub-Saharan Africa	0	0	7750	0	-7750	683127
Malta	294	Middle East & North Africa	0	0	0	0	0	0
Marshall Islands	35	East Asia & Pacific	5	0	0	0	5	0
Martinique	1148	Latin America & Caribbean	781	0	0	0	781	0
Mauritania	1038479	Sub-Saharan Africa	0	0	0	0	0	374003
Mauritius	2145	Sub-Saharan Africa	1700	0	172	0	1527	0
Mayotte	446	Sub-Saharan Africa	351	338	0	0	13	0
Mexico	1956871	Latin America & Caribbean	1103903	11256	85000	104751	987896	3552
Micronesia	516	East Asia & Pacific	438	0	0	0	438	0
Moldova	33688	Europe & Central Asia	26147	0	1500	1600	24547	0
Monaco	9	Europe & Central Asia	0	0	0	0	0	0
Mongolia	1562944	East Asia & Pacific	169788	15855	28581	0	125352	0
Montenegro	13797	Europe & Central Asia	9678	0	0	0	9678	0
Montserrat	113	Latin America & Caribbean	75	58	0	0	17	0
Morocco	672228	Middle East & North Africa	10938	0	16000	0	-5062	0
Mozambique	786342	Sub-Saharan Africa	143277	0	10000	0	133277	595216
Myanmar	667062	East Asia & Pacific	644115	5450	1300	0	637364	0
Namibia	824755	Sub-Saharan Africa	0	0	1228	0	-1228	241718

Nauru	27	East Asia & Pacific	0	0	0	0	0	0
Nepal	147163	South Asia	88549	68	21130	0	67351	22651
Netherlands	34950	Europe & Central Asia	34318	37	0	800	33481	0
New Caledonia	18845	East Asia & Pacific	18131	17848	0	0	283	0
New Zealand	268733	East Asia & Pacific	169756	14040	5000	5270	150446	0
Nicaragua	128105	Latin America & Caribbean	115186	1119	34686	0	79381	0
Niger	1182008	Sub-Saharan Africa	0	0	32000	0	-32000	550596
Nigeria	908526	Sub-Saharan Africa	126423	85	53986	300365	-174027	743084
Niue	250	East Asia & Pacific	232	0	0	0	232	0
Norfolk Island	49	East Asia & Pacific	39	0	0	0	39	0
North Korea	122211	East Asia & Pacific	121607	0	0	0	121607	0
North Macedonia	25463	Europe & Central Asia	19880	0	0	0	19880	0
Northern Mariana Islands	237	East Asia & Pacific	161	0	0	0	161	0
Norway	320887	Europe & Central Asia	121045	25318	0	10000	85727	0
Oman	308652	Middle East & North Africa	0	0	0	0	0	0
Pakistan	876530	South Asia	45893	8	38533	17560	7352	0
Palau	380	East Asia & Pacific	332	0	0	0	332	0
Palestinian Territory	6239	Middle East & North Africa	0	0	42	0	-42	0
Panama	74135	Latin America & Caribbean	69769	507	22184	0	47078	0
Papua New Guinea	461922	East Asia & Pacific	426023	47112	0	0	378912	18402
Paraguay	398806	Latin America & Caribbean	86049	43	0	0	86006	310319
Peru	1290857	Latin America & Caribbean	923989	53530	32000	17880	838460	0
Philippines	292410	East Asia & Pacific	285147	0	0	0	285147	0
Pitcairn	48	East Asia & Pacific	39	0	0	0	39	0
Poland	311670	Europe & Central Asia	311370	0	0	0	311370	0
Portugal	91909	Europe & Central Asia	18031	0	0	0	18031	0
Puerto Rico	9147	Latin America & Caribbean	8569	0	0	0	8569	0
Qatar	11096	Middle East & North Africa	0	0	0	0	0	0
Réunion	2642	Sub-Saharan Africa	2602	86	0	0	2516	0
Romania	237377	Europe & Central Asia	212814	3434	0	0	209380	0

Russian Federation	17005013	Russia	11317436	5666979	0	0	5650457	0
Rwanda	25137	Sub-Saharan Africa	11061	0	22601	15850	-11540	13464
Saint Helena	130	Sub-Saharan Africa	0	0	0	0	0	127
Saint Kitts and Nevis	196	Latin America & Caribbean	49	0	0	0	49	0
Saint Lucia	635	Latin America & Caribbean	573	0	25	0	548	0
Saint Vincent and the Grenadines	342	Latin America & Caribbean	213	0	0	0	213	0
Samoa	2938	East Asia & Pacific	2638	83	0	0	2555	0
Sao Tome and Principe	1142	Sub-Saharan Africa	978	933	320	0	-275	0
Saudi Arabia	1924703	Middle East & North Africa	0	0	0	0	0	0
Senegal	196015	Sub-Saharan Africa	0	0	20000	0	-20000	194371
Serbia	88136	Europe & Central Asia	87919	0	10008	0	77911	0
Seychelles	378	Sub-Saharan Africa	166	0	29	0	137	0
Sierra Leone	72486	Sub-Saharan Africa	46626	0	175	0	46451	18754
Singapore	551	East Asia & Pacific	505	0	0	0	505	0
Slovakia	48927	Europe & Central Asia	48927	171	0	0	48756	0
Slovenia	20421	Europe & Central Asia	18909	0	0	0	18909	0
Solomon Islands	26984	East Asia & Pacific	25549	298	0	0	25251	0
Somalia	636273	Sub-Saharan Africa	30327	0	0	0	30327	484907
South Africa	1220228	Sub-Saharan Africa	29704	0	36000	0	-6296	168902
South Korea	97236	East Asia & Pacific	95527	0	0	62500	33027	0
South Sudan	633188	Sub-Saharan Africa	0	0	0	0	0	0
Spain	498657	Europe & Central Asia	74533	341	0	0	74192	0
Sri Lanka	66039	South Asia	63317	0	2000	0	61317	0
Sudan	1853758	Sub-Saharan Africa	2755	32	225080	0	-222356	1136447
Suriname	144986	Latin America & Caribbean	140168	35036	0	0	105132	599
Svalbard	62905	Europe & Central Asia	0	0	0	0	0	0
Sweden	446025	Europe & Central Asia	386919	128921	3500	0	254497	0
Switzerland	41489	Europe & Central Asia	41489	1903	0	0	39586	0
Syria	188006	Middle East & North Africa	0	0	0	0	0	0

Tajikistan	142428	Europe & Central Asia	0	0	700	0	-700	0
Tanzania	941391	Sub-Saharan Africa	108644	7	136526	0	-27889	722710
Thailand	512281	East Asia & Pacific	499674	3582	40366	0	455726	0
Timor-Leste	15042	East Asia & Pacific	14747	0	5072	0	9676	0
Togo	57118	Sub-Saharan Africa	6204	0	14436	0	-8231	50889
Tonga	462	East Asia & Pacific	318	0	0	0	318	0
Trinidad and Tobago	5010	Latin America & Caribbean	4745	0	0	0	4745	0
Tunisia	155382	Middle East & North Africa	2615	0	0	0	2615	0
Turkey	779988	Europe & Central Asia	406166	42	26858	0	379267	0
Turkmenistan	554528	Europe & Central Asia	0	0	0	0	0	0
Turks and Caicos Islands	299	Latin America & Caribbean	83	4	0	0	79	0
Tuvalu	29	East Asia & Pacific	2	0	0	0	2	0
Uganda	242075	Sub-Saharan Africa	24048	0	84438	28830	-60390	184681
Ukraine	597504	Europe & Central Asia	355958	1687	0	0	354271	0
United Arab Emirates	70364	Middle East & North Africa	0	0	0	0	0	0
United Kingdom	244349	Europe & Central Asia	239396	41	1700	15967	223388	0
United States	9465800	North America	4197680	850192	150000	150000	3197488	76443
Uruguay	177861	Latin America & Caribbean	3	0	25625	0	-25622	177533
Uzbekistan	446610	Europe & Central Asia	0	0	10000	0	-10000	0
Vanuatu	12265	East Asia & Pacific	11616	63	0	0	11553	0
Vatican City	1	Europe & Central Asia	0	0	0	0	0	0
Venezuela	910860	Latin America & Caribbean	561481	243220	2645	0	315616	236110
Vietnam	324278	East Asia & Pacific	307287	349	9650	172356	134582	0
Wallis and Futuna	160	East Asia & Pacific	95	0	0	0	95	0
Yemen	453586	Middle East & North Africa	0	0	0	0	0	0
Zambia	751918	Sub-Saharan Africa	34982	0	24318	0	10665	632411
Zimbabwe	389862	Sub-Saharan Africa	0	0	68078	0	-68078	382965

Appendix 4: Proposed NCS table

Roe et al., 2021	Drever et al., 2021	Strassburg et al., 2020	Griscom et al., 2020	Smith et al., 2019	Fargione et al., 2018	Griscom et al., 2017
Reduce deforestation	Cover crops	Forest restoration	Avoided forest conversion	Afforestation or reforestation (AR)	Reforestation	Reforestation
Reduce mangrove conversion	Cover residue-biochar	Natural grassland restoration	Avoided peat impacts	Wetland restoration	Natural forest management	Avoided forest conversion
Reduce peatland degradation and conversion	Nutrient management	Shrubland restoration	Avoided mangrove loss	Soil carbon sequestration (SCS)	Avoided forest conversion	Natural forest management
Improved forest management	Tree intercropping	Arid ecosystem restoration	Natural forest management	Biochar	Urban reforestation	Improved plantations (forests)
Grassland fire management	Manure management	Wetland restoration	Avoided woodfuel	Terrestrial enhanced weathering (TEW)	Fire management (forests)	Avoided woodfuel
Afforestation and reforestation	Silvopasture		Fire management	Bioenergy with carbon capture and storage (BECCS)	Improved plantations (forests)	Fire management (forests)
Mangrove restoration	Increased legume crops		Trees in agricultural lands		Avoided grassland conversion	Biochar
Peatland restoration	Reduced tillage		Nutrient management		Cover crops	Trees in croplands
Enteric fermentation	Riparian tree planting		Optimal grazing intensity		Biochar	Nutrient management
Manure management	Legumes in pasture		Reforestation		Alley cropping	Grazing-feed
Nutrient management	Avoided conversion of shelterbelts		Peat restoration		Cropland nutrient management	Conservation agriculture
Improved rice cultivation	Avoided peatland conversion		Mangrove restoration		Improved manure management	Improved rice
Agroforestry	Avoided FWM wetland conversion				Windbreaks	Grazing-animal management
Biochar from crop residues	Salt marsh restoration				Grazing optimization	Grazing-optimal intensity
Soil organic carbon in croplands	FWM wetland conversion				Grassland restoration	Grazing-legumes
Soil organic carbon in grasslands	Peatland restoration				Legumes in pastures	Avoided grassland conversion
BECCS	Seagrass restoration				Improved rice	Coastal restoration
Increase clean cookstoves	Avoided seagrass loss				Tidal wetland restoration	Peat restoration
Reduce food waste	Avoided grassland conversion				Peatland restoration	Avoided peat impacts

Shift to sustainable healthy diets	Riparian grassland restoration				Avoided seagrass loss	Avoided coastal impacts
	Improved forest management				Seagrass restoration	
	Avoided forest conversion					
	Restoration of forest cover					
	Urban canopy cover					

Appendix 5: Climate mitigation potential per NCS

	Griscom et al., 2017 (until 2030)		**Drever et al., 2021** (until 2030)		**Griscom et al., 2020** (2030-2050, cost effective)		**Fargione et al., 2018** (in 2025)	
	$TgCO_2eyr^{-1}$	%	$TgCO_2eyr^{-1}$	%	$TgCO_2eyr^{-1}$	%	$TgCO_2eyr^{-1}$	%
Agroforestry	616	2,593684	3,9	5,019305	930,82	14,24274	82	6,812329
Natural regeneration	220	0,926316		0		0		0
Avoided forest conversion	3603	15,17053	3,8	4,890605	2826,42	43,24785	38	3,156933
Avoided grassland conversion	116	0,488421	12,7	16,34492		0	107	8,889258
Reforestation	10124	42,62737	<0,1	0,1287	1167,04	17,85721	307	25,50469
Grassland restoration		0		0		0	9	0,747695
Fire management	212	0,892632		0	26,87	0,411145	18	1,495389
Grazing management	1175	4,947368		0	27,31	0,417878	11	0,913849
Natural forest management	1470	6,189474					267	22,18161
Improved plantations	443	1,865263	7,9	10,16731	516,17	7,898063	12	0,996926
Silvopasture		0	2,8	3,603604		0		0
Avoided woodfuel harvest	367	1,545263		0	77,52	1,186155		0
Biochar	1102	4,64	6,9	8,880309		0	95	7,892332
Cropland nutrient management	706	2,972632	6,3	8,108108	124,59	1,906387	52	4,320013
Conservation agriculture	413	1,738947		0		0		0
Windbreaks (trees in croplands)	204	0,858947		0		0	11	0,913849
Improved rice cultivation	265	1,115789		0		0	3,7	0,307386
Avoided coastal wetland impacts	304	1,28		0		0		0
Avoided peatland impacts/avoided peatland conversion	754	3,174737	10,1	12,99871	566,26	8,664504		0
Coastal wetland restoration	841	3,541053		0		0		0
Avoided mangrove loss				0	59,91	0,9167		0
Mangrove restoration				0	5,2	0,079567		0
Tidal wetland restoration				0			12	0,996926
Peatland restoration	815	3,431579		0	234,16	3,582948	9	0,747695

Cover crops	9,8	12,61261		0	103	8,556949
Manure management	3	3,861004		0	24	1,993852
Increased legume crops	2,6	3,346203		0		0
Reduced tillage	0,9	1,158301		0		0
Riparian tree planting	0,7	0,900901		0		0
Legumes in pasture	0,2	0,2574		0	7	0,58154
Avoided conversion of shelterbelts	0,2	0,2574		0		0
Avoided freshwater mineral wetland conversion	3,1	3,989704		0		0
Salt marsh restoration	1,5	1,930502		0		0
Freshwater mineral wetland restoration	0,4	0,514801		0		0
Seagrass restoration	<0,1	0,1287		0	6	0,498463
Riparian grassland restoration	0,7	0,900901		0		0
Urban canopy cover/reforestation	0,2	0,2574		0	23	1,910775
Avoided seagrass loss		0			7	0,58154

Appendix 6: Literature research case studies

From NbS bibliography selection (University of Oxford, 2021)

Article	**NCS**	**Country**	**Climate mitigation**	**Biodiversity**	**Social factors**	**Other ecosystem services/water**	**Location**	**Theoretical or empirical**	**Terrestrial ecoregion**
Lan et al., 2021	Afforestation	China	No significant increase of deep soil carbon	Not reported	Not reported	Water depletion	Gaoxigou Village (37.87N, 110.18 E)	Empirical	Montane grasslands and shrublands
Ullah et al., 2021	Afforestation	Pakistan	Not reported	Positive and negative opinions of the project given	Positive and negative opinions of the project given	Positive and negative opinions of the project given	Dir Kohistan forest (35°9′ - 35°47′ N, 71°52′ -72°22′ E)	Empirical	Montane grasslands and shrublands; Deserts and xeric shrublands; Temperate coniferous forests
Khan et al., 2017	Agroforestry	Pakistan	Not reported	Not reported	Majority of the farmers were positive about implemented agroforestry	Not reported	Bhakkar district; Punjab province	Empirical	Deserts and xeric shrublands
Fadina & Barjolle, 2018	Agroforestry	Benin	Can sequester carbon	Can protect biodiversity	Socioeconomic benefits	Soil conservation	Zou department	Empirical	Tropical and subtropical grasslands, savannas and shrublands
Costa et al., 2018	Agroforestry (crop-livestock-forest (CLFi) and crop livestock (CLi) systems)	Brazil	Reduction of CO_2 emissions (2389 t of CO_2 equivalent) compared to conventional systems	Positive effects compared to conventional systems	Compared to conventional systems, quality of employment improved and investments in future generations promoted	Not reported	Ipameri (17° 39′ 29.47″ S, 48° 12′ 23.51″ W)	Empirical	Tropical and subtropical grasslands, savannas and shrublands
Pandit et al., 2019	Agroforestry (market oriented system)	Nepal	Not reported	Not reported	Household income was increased by 37-48%	Not reported	Chaubas, Mithinkot and Dhungkarka, Kavre district and Nalma, Jita Taxar and	Empirical	Temperate broadleaf and mixed forests; other ecoregions close

							Dhamilikuwa, Lamjung district		
Belem et al., 2017	Assisted natural regeneration (by fencing)	Burkina Faso	Not reported	Increase of species and number of trees	Reduction of poverty	Not reported	Sanmatenga (middle), Boulkiemdé, Kadiogo, Kourwéogo, Oubritenga, Soum, Loroum	Empirical	Tropical and subtropical grasslands, savannas and shrublands
Lalani et al., 2018	Conservation agriculture	Syria	Not reported	Not reported	Livelihood advantages for farmers by improving yields	Improved soil quality	Salamieh district	Empirical	Temperate grasslands, savannas and shrublands
Chan et al., 2017	Conservation agriculture	India	Not reported	Not reported	Food security improved and increased farmers´ resilience; also gender equity is enhanced	Soil conservation	Keonjhar	Empirical	Tropical and subtropical dry broadleaf forests
Sarma et al., 2013	Ecological management practices in hilly urban watersheds	India	169.81 tonnes/year	Not reported	Not reported	Not reported	Guwahati (26°6′30″N, 91°47′20″E)	Theoretical	Tropical and subtropical moist broadleaf forests
Wiedin myer & Hurteau , 2010	Fire management (prescribed fire)	United States	Reduction of CO^2 emissions compared to wildfires	Smaller tree mortality than from wildfire	Not reported	Not reported	Western United States	Theoretical	Mix
Huang et al., 2014	Grassland restoration	China	0,346 MtC sequestered in the first period (1990-2004), and 1,537 MtC in the second (2004-2012)	Coverage of grassland vegetation increased	Not reported	Not reported	Tibetan plateau (95 E, 35 N)	Empirical	Montane grasslands and shrublands
Zhang et al., 2017	Grassland restoration to limit sand erosion	China	1.7% increase of SOC, although large variation across methods. At least 55.5	Not reported	Not reported	Not reported	Xilingol grassland (41°32′–46°41′N,	Empirical	Temperate grasslands, savannas and shrublands

			years needed for the grassland to reach maximum carbon stock				111°6′–120°10′E)		
Salete Capellesso et al., 2021	Natural regeneration	Brazil	Carbon stock increases up to 80 years at least	Species richness increases	Not reported	Not reported	Guaricica Nature Reserve (25°19′S, 45°42′W), das Águas Nature Reserve (25°21′S, 48°46′W)	Empirical	Tropical and subtropical moist broadleaf forests
Bourne et al., 2017	Rangeland restoration	South Africa	Not reported	Treatments did not succeed in increasing species richness	Not reported	Not reported	Nama Khoi, (28° 59′ 26.1852″ - 29° 12′ 51.9834″ S, 17° 41′ 27.744″E - 18° 13′ 10.9698″ E)	Empirical	Deserts and xeric shrublands
Warner et al., 2021	Reforestation	Scotland	In early stages of reforestation, reforestation may lead to soil carbon losses. Topsoil carbon was 18.78 kg/m2 compared to 29.82 kg/m2 in unforested plots and 31.39 kg/m2 in mature forest	Native species planted, but not all old species (ericaceous shrubs and moss layer) returned	Not reported	Not reported	Glen Affric (57°12′50″N, 05°13′48″W - 57°17′15″N, 004°56′04″W) and Glen Moriston (57°12′28″N, 004°50′54″W - 57°13′23″N, 004°43′32″W)	Empirical	Temperate coniferous forests
Scheidel & Work, 2018	Reforestation	Cambodia	Carbon stock reduced through logging, carbon sequestration of plantation unknown	Diverse forest landscape was converted to acacia monocultures	1500-2000 people affected negatively; employment dropped		Prey Long forest	Empirical	Tropical and subtropical dry broadleaf forests
Lin et al., 2012	Reforestation	China	Significant increase for plantation	Ecological impacts are described to be positive, forest	mostly positive', 'net income for farmers was almost 6 times	water holding capacity was 25.2% higher and heavy	Poyang Lake basin (24°29′ - 30°04′N,	Empirical	Tropical and subtropical moist broadleaf forests;

			forests, from 2.29 TgC/year to 10.52 TgC/year (but this is only for the new forests)	cover increased by tree planting (!); from 40.30% in 1949 to 35.89% in 1988 to 60.05% in 2005. But no reports on species diversity	greater, number of people living below the poverty line decreased from 10 million to 0.865 million'	and severe soil erosion decreased by 55.2 and 53.6 %'	113°34' - 118°28'E)		Temperate broadleaf and mixed forests
Pires et al., 2017	Reforestation	Brazil	14 GtCo2yr-1ha-1	will facilitate ecological restoration	social and economical benefits	improve water quality	Rio Doce watershed (19.5;-42)	Theoretical	Tropical and subtropical moist broadleaf forests
Hani et al., 2017	Reforestation	Lebanon	Not reported	Native species used and natural vegetation was kept intact	Providing work and income for refugees	No watering needed	Shouf Biosphere Reserve (35º 28'- 35º 47' E, 33º 32'- 35º 48' N)	Empirical	Mediterranean forests, woodlands, and shrublands
Schirone et al., 2011	Reforestation (Miyawaki application)	Italy	Not reported	Plant biodiversity appears high	Not reported	Not reported	Pattada, Sardinia	Empirical	Mediterranean forests, woodlands and shrubs
McElwee et al., 2017	Reforestation	Vietnam	Not reported	Not reported	Negative impacts on livelihoods have been reported in adaptation and resilience to climate change; policies did not take into account the needs of local communities	Not reported	Dien Bien, Kon Tum and Kien Giang provinces	Empirical	Tropical and subtropical moist broadleaf forests
Rana & Miller, 2021	Reforestation (tree planting)	India	Not reported	Positive in some cases, negative in others	Positive in some cases, negative in others	Not reported	Kangra; Himachal Pradash	Empirical	Boreal forests/taiga; Montane grasslands and shrublands; Temperate broadleaf and mixed forests
Wheeler et al., 2016	Reforestation, by replanting native species and	Uganda	Sequestration of above ground carbon increased	Number of seedling species increased, but still	Not reported	Not reported	Kibale National Park(E 30.31–30.36, N 0.31–0.56)	Empirical	Tropical and subtropical moist broadleaf forests

	protection from fire			lower than old-growth forest					
Schmied el et al., 2017	Restoration; check dams; gully treatments; soil erosion control; revegetation	South Africa	Carbon sequestration	Biotic variables 10-30 times higher'	Not reported	Increased vegetation cover and soil depth	farm Avontuur, Bokkeveld plateau (31°15′37″S, 19°04′04″E)	Empirical	Deserts and xerix shrublands
Andrade et al., 2009	Silvopasture	Costa Rica	Carbon sequestration in soil organic carbon and woody biomass increased	Not reported	Not reported	Not reported	Hacienda La Pacifica (85°9′14.5″ W, 10°28′36.8″N)	Empirical	Tropical and subtropical dry broadleaf forests

From own literature list

Article	NCS	Country	Climate mitigation	Biodiversity	Social factors	Other ecosystem services/water	Location	Theoretical or empirical	Terrestrial ecoregion
Hajdu et al., 2016	Afforestation	Uganda	Not reported	Not reported	Project failed to include social science. Local livelihoods however are not the main focus of the research.	Not reported	Kachung	Empirical	Tropical and subtropical grasslands, savannas, and shrublands
Rampra sad et al., 2020	Afforestation	India	Not reported	Forest cover increases	Plantations change livelihoods and increase vulnerability of pastoralists, who could not influence the design of the projects	Not reported	Kangra, Himachal Pradesh (32N, 77E)	Empirical	Temperate broadleaf and mixed forests; montane grasslands and shrublands; tropical and subtropical coniferous forests
Jiao et al., 2010	Afforestation	China	Not reported	Species diversity increased compared to non-	Not reported	Soil erosion reduced and soil nutrients increased	Zhifanggou watershed (109◦ 14′ 09″ -	Empirical	Temperate broadleaf and mixed forests;

				afforested croplands; However this is not the original vegetation and on the long term will not enhance biodiversity		compared with non-afforested grasslands but not compared to natural areas	109◦ 16′ 01′′ E, 36◦ 43′ 11′′- 36 ◦46′25′′ N)		montane grasslands and shrublands
Haglund et al., 2011	Farmer Managed Natural Regeneration (FMNR)	Niger	Not reported	Density and diversity of trees is increased	Household income is increased	Not reported	Maradi	Empirical	Tropical and subtropical grasslands, savannas, and shrublands
Russel-Smith et al., 2015	Fire management	Australia	Carbon sequestration and reduction of GHG emissions	Benefits for biodiversity	Well-being of local communities enhanced	Other benefits to ecosystem health	Kakadu, Litchfield and Nitmiluk National Parks	Empirical	Tropical and subtropical grasslands, savannas, and shrublands

Appendix 7: Location case studies